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The Potential Impact of MMICs On Future Satellite Communications - Technology Assessment

FINAL REPORT

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Cleveland, Ohio 44135

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1.0 INTRODUCTION

During the past ten years dramatic strides have been made in the technology of Gallium Arsenide Monolithic Microwave Integrated Circuits (GaAs MMICs). These developments have demonstrated the potential of this technology for opening up new systems opportunities by making it possible to accomplish microwave circuit functions in a physical size or at a cost which would be unattainable using conventional microwave circuit technology. This technology has obvious potential benefit for space-based equipment because of its ability to reduce radically the size and weight of microwave circuitry, and its capability for realizing functions which would be impractical with conventional techniques.

The purpose of this study is to identify the potential space communication applications of MMICs, assess the potential impact of MMICs on the classes of systems identified, determine the present status and probable ten-year growth in capability of required MMIC and competing technologies, identify the applications most likely to benefit from further MMIC development, and present recommendations for NASA development activities to address the needs of these applications.

The relationship among these tasks is illustrated graphically in Figure 1-1. The survey of upcoming satellite communication requirements results in the identification of potential MMIC applications, based on criteria such as the number of identical circuits required by the application, their complexity, the potential benefit from size reduction, performance, cost, frequency, and the importance of uniformity. For each of these identified applications, an attempt is made to define the circuit requirements as explicitly as possible. At the same time an assessment of MMIC technology and competing technologies is made.

All of the above results are then used to assess the potential of MMICs for the identified applications. Applications most likely to benefit from focused development are identified based on such rationale as improvement in system economic performance, enabling technology for the mission, or improved technical performance. Cost benefits are quantified where possible.

Finally recommendations are made for NASA development activities based on such criteria as time scale, priority among recommended programs, estimate of economic benefit versus development cost, and relationship to other known development activities.

1.1 BACKGROUND

Monolithic microwave integrated circuits are defined here, in what has become the conventional way, as circuits in which all active elements and their associated passive elements and interconnections are formed in to the bulk, or on to the surface, of a semi-insulating substrate by semiconductor processing techniques such as epitaxy, ion implantation, sputtering, evaporation, etc.(1)

MMIC technology began in the mid-1960s with an Air Force funded program to develop transmit-receive modules for an aircraft phased-array radar. Because of the time at which this work was done, it was based on silicon technology. The results were disappointing primarily because of the inability of the silicon to maintain its semi-insulating properties through the high- temperature diffusion processes. The resulting substrates were lossy and the microwave performance was poor. As a result there was little further activity until the mid-1970s when developments in Gallium Arsenide MESFETs (MEtal-Semiconductor Field Effect Transistors) made it possible to overcome many of the problems which had plagued the earlier attempts at silicon-based MMICs. With the rapid development of the MESFET as the superior active device from about C-band into the millimeter wavelengths, and the demonstration that semi-insulating Gallium Arsenide is an excellent substrate for microwave circuitry, the stage was set for the widespread development of Gallium Arsenide-based MMICs.

1.2 ADVANTAGES AND DISADVANTAGES OF THE MMIC APPROACH

Many of the advantages of the monolithic approach can be appreciated by considering a microwave amplifier constructed using hybrid microwave integrated circuit (MIC) techniques, the more conventional approach which the MMIC technique attempts to replace. Figure 1-2 is a photograph of a state-of-the-art hybrid MIC amplifier, using the most advanced techniques of hybrid MIC construction. The active devices, dual-gate FETs in the case of this variable-gain amplifier, are unpackaged GaAs chips brazed to the metal housing and connected to the associated circuitry by means of wire bonds. The matching circuitry is etched in thin-film metalization on alumina substrates which are also brazed to the housing. The required capacitors are chip components soldered to the housing or to the substrates. The resistors in this case are etched in tantalum nitride metalization on the substrate, but in many hybrid MIC circuits the resistors are also chip components bonded to the substrate. Tuning adjustments can be made to the amplifier by bonding or not bonding to extra tabs etched in the metalization. As a final step, the amplifier is hermetically sealed to protect the active devices by welding a lid on to the package.

As a simple comparison an MMIC amplifier is shown in Figure 1-3. Like Figure 1-2, this is a two-stage amplifier using two FETs, but in this case both FETs and all of their associated circuitry are on the same GaAs chip. Capacitors are MIM capacitors fabricated on the substrate.

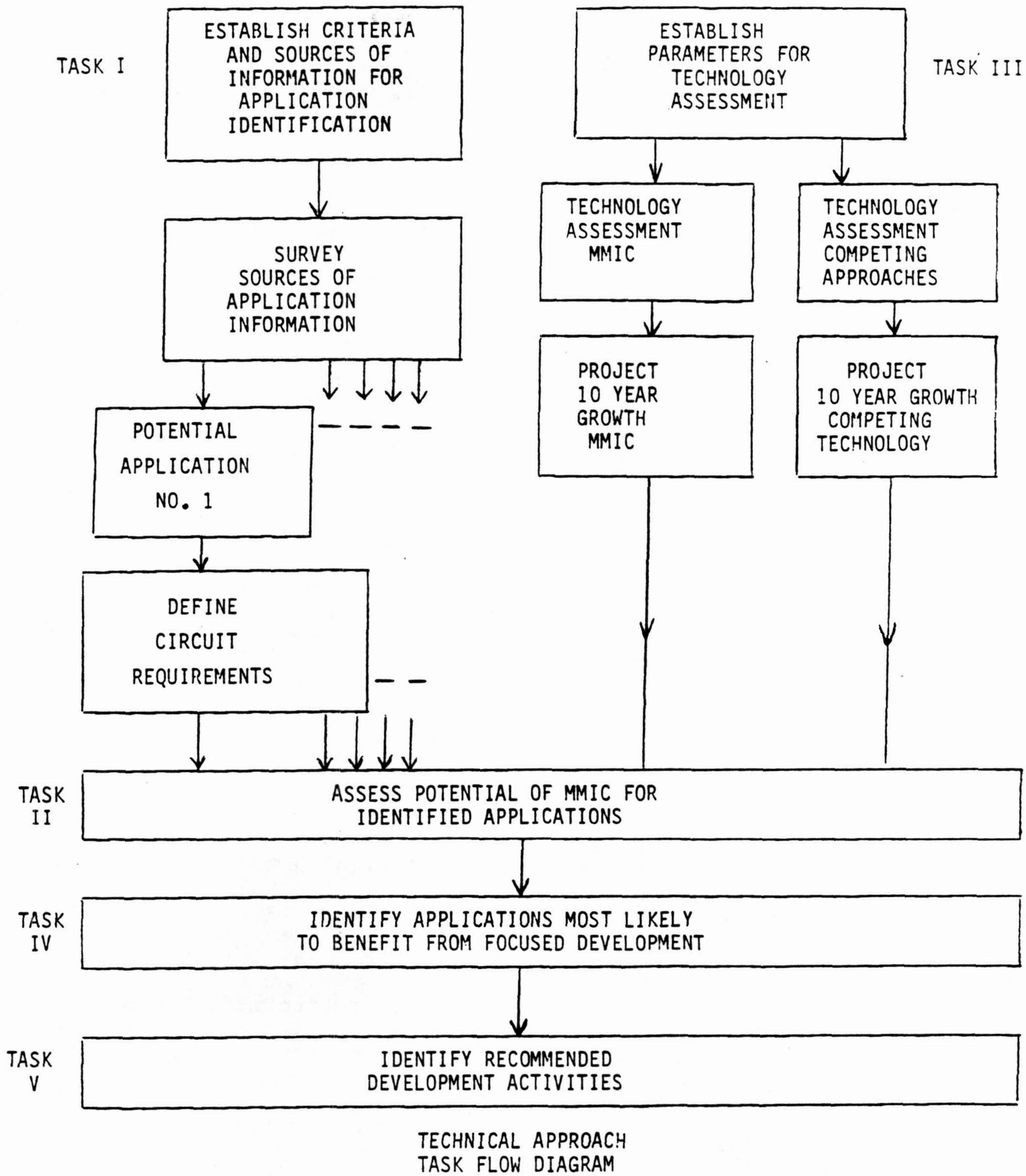

FIGURE 1-1 Technical Approach - Task Flow Diagram

Air bridges are used for cross-overs when needed and ground connections are brought to the circuitry on top of the substrate by means of plated vias. This amplifier chip was fabricated along with many other circuits on a three-inch diameter Gallium Arsenide substrate like the one shown in Figure 1-4. There would have been room for over one-thousand of these 3.0 by 1.3 millimeter amplifier chips on the GaAs wafer if it had been entirely dedicated to this particular circuit. Figure 1-5 is a photograph of the MMIC and hybrid amplifiers side by side.

A comparison of these two realizations of a two-stage amplifier reveals many of the advantages and disadvantages of the MMIC approach.

The MMIC version is, of course, much smaller. Even after taking in to account that the MMIC amplifier is for 20 GHz while the hybrid amplifier operates at 12.5 GHz, the MMIC unit is substantially smaller. This is partly because of the high dielectric constant of Gallium Arsenide, but it is also due to the elimination of unnecessary interconnections and the ability to fabricate circuit elements such as the capacitors and their interconnections in a much smaller size using semiconductor processing techniques. A very significant difference is that the active device is fabricated in intimate association with the circuitry in a way that is precisely repeatable in the case of the MMIC, whereas in the hybrid approach wire bonds must be used to connect the gate, drain, and source of the devices to the circuit. These are very critical connections and at frequencies such as X-band and above the reactance of these wires form a significant portion of the circuit. In addition, the connection to the ground of the microstrip is through the brazed connection of the substrate to the housing. The inability to make these connections sufficiently repeatable is one of the major reasons that the hybrid amplifier must be tuned, consuming expensive skilled manpower as well as making it necessary to make the circuit large enough to permit tuning. Thus, the assembly of the hybrid unit is expensive and time consuming because of the many critical connections that must be made, and the inevitable variations in assembly necessitate expensive and time consuming tuning adjustments.
Aside from the variability the interconnections introduce, their very presence in many cases is a serious limitation on the performance which can be achieved, particularly in terms of bandwidth. These problems rapidly become more severe as frequency is increased. Whereas they can be an important cost factor at X-band, they can make the circuit completely unproduceable at millimeter wavelengths.

The elimination of the many wire bonds and interconnects lead to another important advantage of the MMIC approach: reliability. The wire bonds of the hybrid approach seriously degrade the reliability of the circuit.

Advantages in circuit design and functionality accrue from the fact that the MMIC approach makes the use of active devices much less expensive. The incremental cost of adding an additional FET to an MMIC is small, mainly the cost attributable to whatever decrease in yield

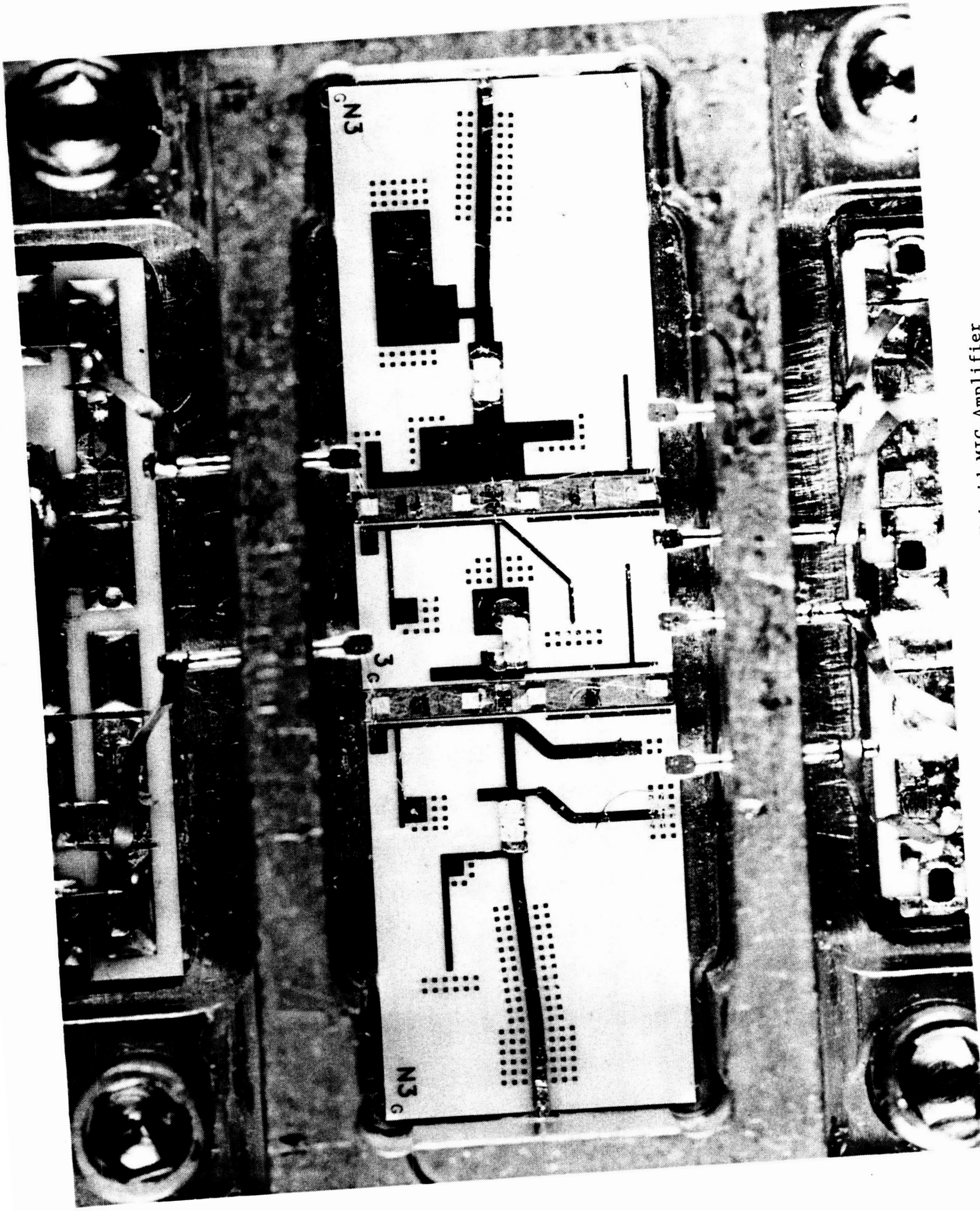

FIGURE 1-2 Stare-of-the-art Hybrid MIC Amplifier

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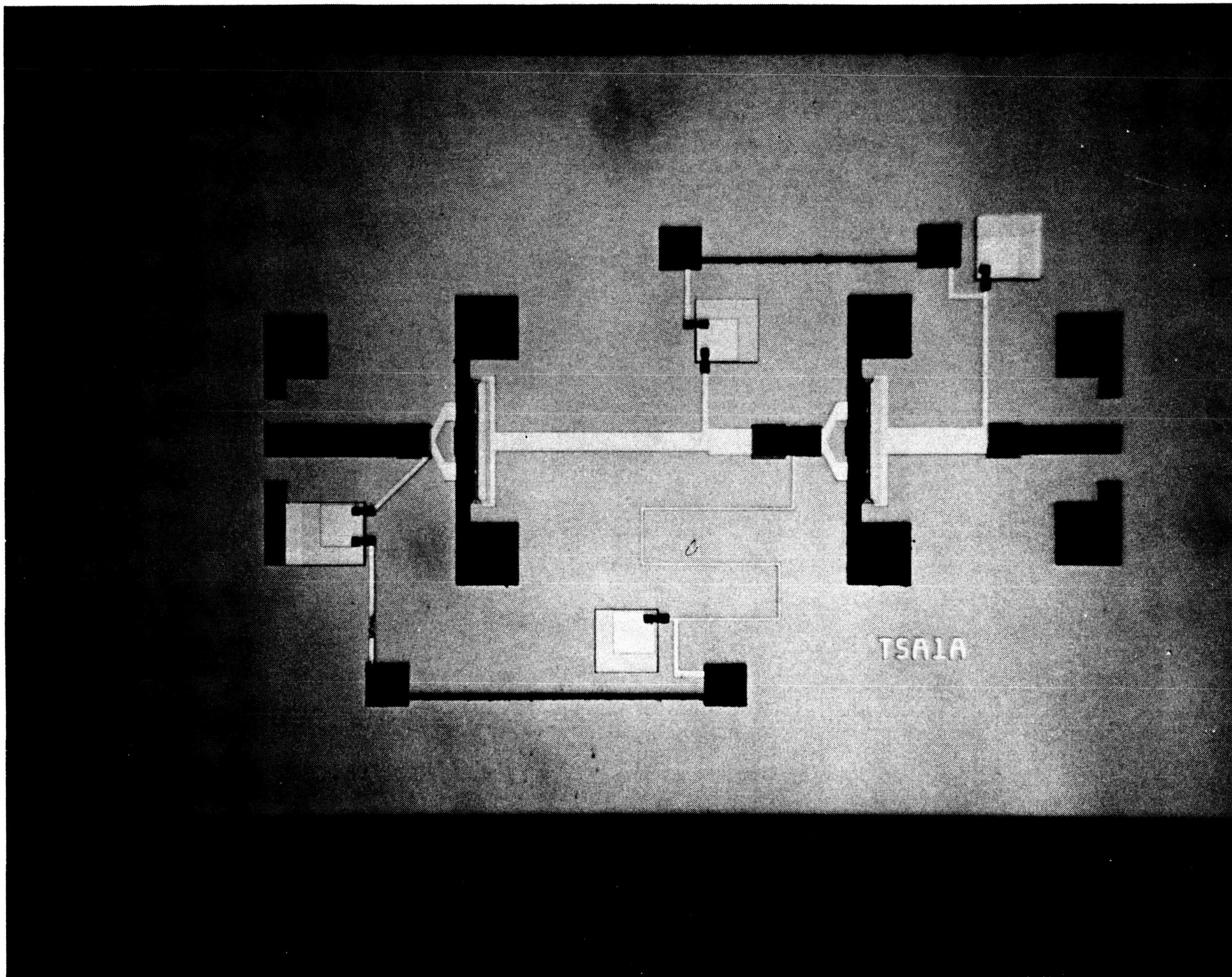

FIGURE 1-3 A Two-Stage MMIC Amplifier

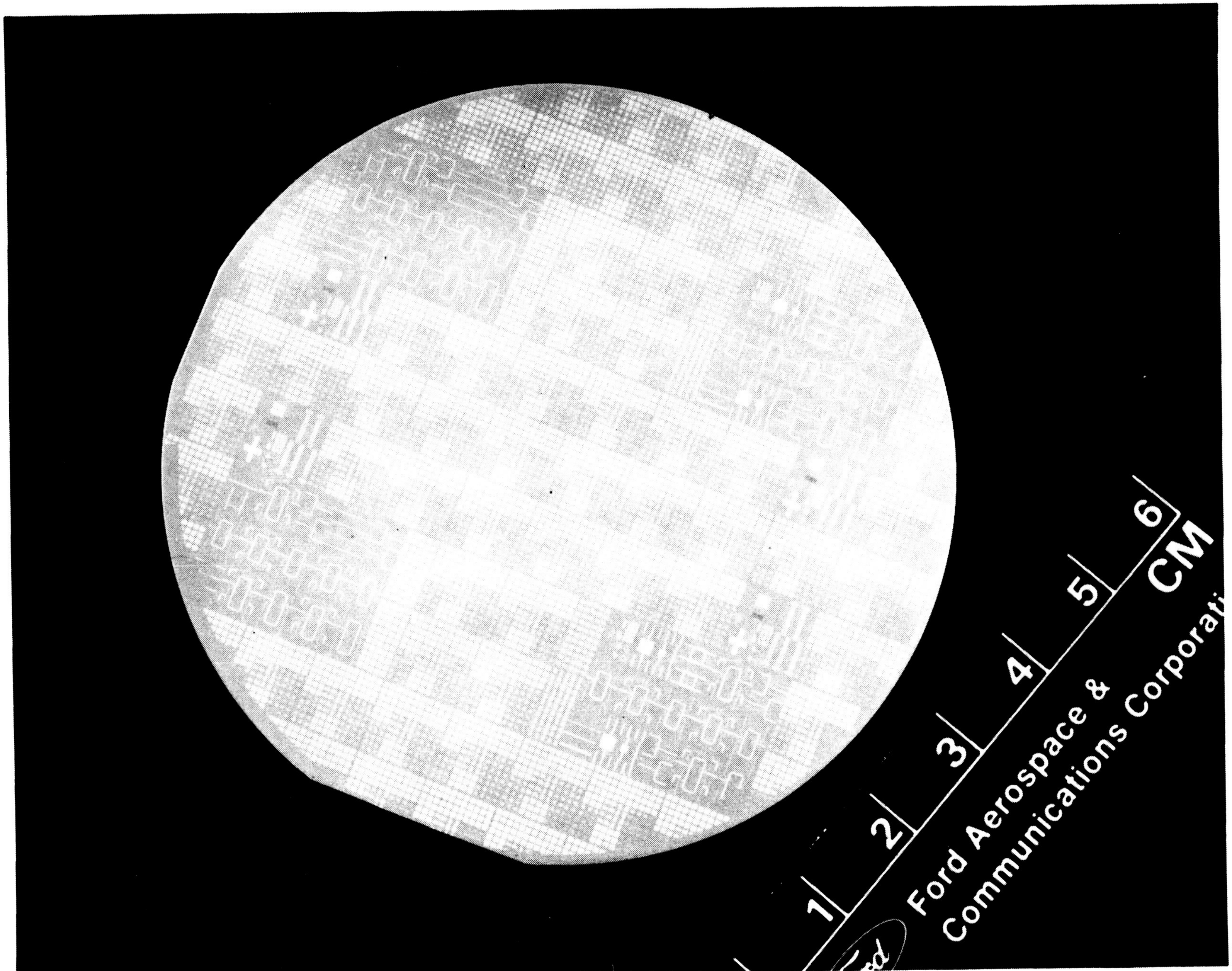

FIGURE 1-4 A Three-inch Diameter GaAs Wafer Containing A Variety of Monolithic Circuits And Devices

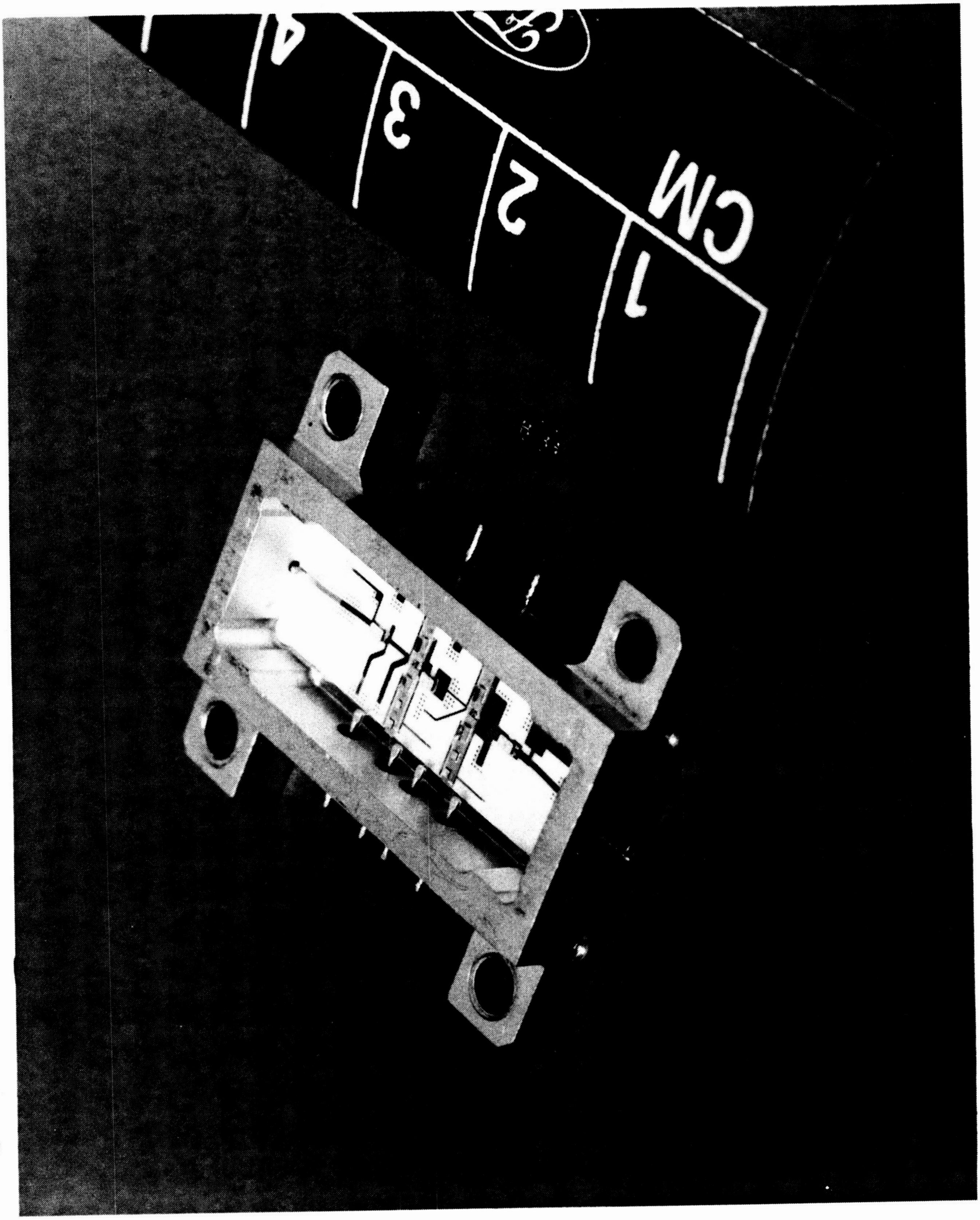

FIGURE 1-5 Hybrid MIC And MMIC Two-Stage Amplifiers

results from the additional active device and the cost of the additional GaAs area. As a result circuit designs which are extravagant in the use of active devices, such as broadband distributed amplifiers, become more practical with the MMIC technology.

Thus, the major advantages of the MMIC approach are:

- Low production cost through batch fabrication
- Small size
- Reliability
- Permits the use of large numbers of active devices

Some other attributes of MMICs are important in particular applications. For example, active arrays require that all of the large number of active modules have nearly identical performance which tracks well from unit to unit over temperature. This is more readily accomplished with MMICs where a large number of identical circuits can be made from one GaAs wafer.

There are disadvantages, also, to the MMIC approach. First, and in many cases most important, the development of an MMIC circuit is costly and time consuming. Although these factors can vary widely depending on the circuit and its similarity to previous designs, the development of a new relatively sophisticated circuit can typically consume several hundred-thousand dollars and a year or two of time. This may not be justified unless the development cost can be spread over a large number of production units, or unless there are substantial size, weight, or performance benefits from the MMIC approach. Also, while the MMIC approach can sometimes produce better performance by eliminating parasitics, for instance in broadband amplifiers, in some cases the performance is inferior. A hybrid circuit can be tuned to maximize the performance, while an MMIC may have an economical yield only if a significant margin is allowed between the specification and optimized performance, or if design techniques such as feedback are used which sacrifice some performance for insensitivity to process variations. In addition, the losses of the MMIC matching circuits don't allow MMICs to achieve the lowest possible noise figures or highest power outputs.

Table 1-1 summarizes some important advantages and disadvantages of the MMIC approach.

1.3 OVERVIEW OF MICROWAVE CIRCUITS FOR SPACE APPLICATION

Several general observations can be made about the microwave circuit requirements for space applications. First and foremost, of course, is that an extremely high premium is put on reliability. Second, minimizing size and weight is an important objective. These considerations are strong arguments in favor of the MMIC approach. On the other side of the ledger, microwave assemblies for space applications are usually required only in very small quantities, so the development costs for custom designs cannot be spread over a large

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quantity. The benefit of the MMIC must be sufficient to justify the development for only a small quantity of units. The argument that the batch fabrication of MMICs leads to low large quantity cost is not generally a reason to use MMICs in space. Finally, microwave components for space are often performance driven with the best possible performance required, even if this means large amounts of expensive tuning and optimization.

Thus, considering the nature of the requirements only in these general terms, there are arguments both for and against the MMIC approach. Whether on not the approach is beneficial depends on the requirements of the specific application.

TABLE 1-1

SUMMARY OF THE ADVANTAGES AND DISADVANTAGES OF THE MMIC APPROACH

ADVANTAGES OF MMIC APPROACH	DISADVANTAGES OF MMIC APPROACH
* Small size * Light weight * Low quantity cost through batch fabrication * Reliability * Makes it practical to use large number of active devices * Capability for large bandwidth * Good tracking from unit to unit	* Expensive in small quantity if custom design required * Does not achieve as low noise figure as best hybrid circuits * Does not achieve as high power or efficiency as best hybrid circuit

1.4 OVERVIEW OF SATELLITE REQUIREMENTS

This study will take a detailed look at the present and projected capabilities of MMIC technology and relate it to anticipated space requirements to see where this technology can have a significant impact on capabilities in space. In the satellite communication area in particular, the market is changing rapidly under the influence of several technological and regulatory developments, and the application of MMIC technology must be looked at in the context of these external changes.

One of the most important changes effecting the satellite communication business is the great success of fiber optic cables for long distance communication. The dramatic advances in fiber optic capability has made it the technology of choice for much long distance two-way communication. For fixed point-to-point communication fiber optic cable has advantages over satellite service for dense traffic over links less than a certain distance. As performance of optic cables has improved, the crossover point between optics and satellites, in

terms of traffic density and distance, has moved, capturing more of the business for optic cable.

However, communication satellites have crucial advantages over competing technologies in several important areas such as point-to-multipoint communication, communication over thin routes and to remote areas, mobile communication, and communication which bypasses local telephone companies to provide customer premises service through very small aperture satellite terminals (VSATs).

Customer premises service through VSATs is a rapidly growing satellite service. At the present this service is primarily for data distribution and uses a two hop type of network in which data is transmitted from one VSAT to the satellite, from the satellite to a master ground station for regeneration and distribution, from the master station back to the satellite, and finally from the satellite to the destination VSAT. This two-hop approach is generally not acceptable for voice traffic because of the one-half second delay. Satellite technology which would eliminate the second hop by performing the functions of the master earth station on board the satellite would make practical the use of VSATs for voice traffic and greatly increase the usefulness of VSATs.

Another factor which will influence communication satellite requirements is the implementation of the Integrated Services Digital Network (ISDN) standards formulated by the CCITT (International Consultive Committee on Telephony and Telegraphy), and designed to facilitate the implementation of dial-up digital access throughout the world. Among other things the imposition of this standard will more than double the spectrum requirements for the same number of users.(2)

Still another factor that must be considered in considering communication satellite technology is availability of space in the geo-stationary arc. This is a limited resource and increasing communication needs will make it important to develop satellite technology which will make most efficient use of it.

The requirements for communication satellites are also being affected significantly by the recent difficulties with launch vehicles. Increasing insurance rates and the increasing risks of investing in a communication satellite, are hurting the satellite's ability to compete with fiber optic cable in many applications.

Finally, the satellite communication business, like all communication operations, is being affected in many parts of the world by the sort of deregulation which has impacted the communication business in the United States.

All of these general considerations establish the context in which communication satellite technology developments must be considered.

2.0 SURVEY OF SPACE APPLICATIONS

The first task of this project was to identify potential space communications applications of MMIC technology in the areas of commercial, military, and government non-military satellite communications. The areas to be considered in the assessment were to include all foreseeable commercial, military, and government non-military applications of space communications; and the technology areas to be considered were to include, but not be limited to, all microwave, optical, intermediate frequency, and baseband technologies judged to be, or likely to become, relevant to space communication systems. When the study was approximately half-way completed, the contractor was requested by the Program Manager to deemphasize military requirements in order to concentrate attention on NASA requirements.

2.1 EVALUATION CRITERIA

In order to focus the survey of space applications, it was important to first establish some criteria reflecting the particular characteristics and attributes of MMIC technology. It was decided that in the survey of possible MMIC applications, the applications should be considered in the light of the following characteristics of MMICs:

- <u>Potential benefit from size and weight reduction.</u> - One of the clearest benefits of the MMIC approach is the dramatic size and weight reduction it leads to in the microwave circuitry. An application where the size and weight have high leverage either on the cost or on the technical capability will be a clear candidate for MMIC application.

- <u>Number of identical circuits required.</u> - The MMIC approach is particularly attractive in applications where a large number of identical circuits are needed, because of the batch fabrication nature of the process. On the other hand, the development costs of a new MMIC design are greater than for a hybrid MIC design so that if the number of circuits required is small, the cost of the MMIC version can be high.

- <u>Circuit complexity.</u> - The MMIC approach has its greatest advantage in fairly complex circuits having a large number of active and passive elements. It can be an enabling technology in the sense that it can make it possible to place circuit complexity on board the spacecraft which would be impractical with conventional technology.

- <u>Performance.</u> - The electrical performance requirements of the application are important parameters in determining the applicability of MMICs, with some "high performance"

specifications (eg, low noise or high power) being arguments against MMICs while some (eg, wide bandwidth) favor MMICs.

- Frequency. - This is an important consideration in determining MMIC applicability. Millimeter wavelengths present some of the strongest motivations for MMICs because reproducability is so difficult to achieve with conventional techniques, but MMIC techniques are considerably more well established at microwave frequencies.

- Importance of Uniformity. - The monolithic approach is particularly attractive for applications where uniformity from unit to unit is important.

- Cost. - Generally cost will be an argument in favor of the monolithic approach if quantities are large, and against if quantities are small.

- Radiation Hardening. - GaAs MMICs are inherently less susceptible to radiation effects than other types of microwave circuitry, and in addition their small size reduces the weight penalty of shielding.

These MMIC considerations, then, imply system characteristics which must be considered in the survey as determinators of the applicability of MMICs. These systems characteristics which are particularly significant as indicators in the survey are:

- Frequency and Bandwidth of the system

- Type of Antenna (Scanning spot beam? Multibeam? Fixed beam?)

- Performance Parameters (eg Transmitter Power Output, Receiver Noise Figure)

- On-board Signal Processing Requirements

- Efficiency and Power Consumption Constraints

- Size and Weight Constraints

- Requirements for Radiation Hardening

The nature of the antenna system required for the satellite is important because of the applicability of MMICs to active arrays. Active arrays, either phased arrays or arrays of elements for a multibeam antenna, require large numbers of receive or transmit modules. They must meet tight size constraints determined by the

physics of the array. They must be highly repeatable so that the elements will exhibit good tracking from unit to unit over frequency and temperature. They must be inexpensive if the system is to be cost effective. These requirements become more difficult to meet as frequency is increased since the required size of the circuit decreases and the effect of circuit parasitics and wire bonds become more severe making conventional techniques labor intensive and expensive. Therefore, systems which use scanning spot beams for frequency reuse or multibeam antennas for antijam capability are likely to be benefited significantly by MMICs.

Satellites with much on-board complexity, for instance for switching or signal processing, are likely to benefit from monolithic technology or even be impractical without it. Unusual size and weight constraints, or unusually high premiums on weight reduction, call for MMICs. As mentioned before, MMICs have low susceptibility to radiation and, in addition, because of their small size can be easily shielded. Therefore, they may be required to satisfy needs for radiation hardening.

2.2 SOURCES OF INFORMATION FOR SURVEY

In order to identify potential space communication applications of MMICs, an extensive study was made of anticipated NASA space missions, military needs for space-based communications, and projections for commercial applications of space. This was accomplished by reviewing many published reports, studies, and projections, and by personal contacts and interviews.

The major written reports and studies used in this survey are summarized in Table 2-1. Individuals who were contacted personally are identified in Table 2-2.

Among the publications listed in Table 2-1, the Technology Roadmap has been in the past a valuable source of information on requirements and technology development programs addressing these needs. The latest Roadmap, unfortunately, is now rather dated. As a result the Space Communications Technology Assessment, prepared for the Air Force Space Technology Center and the Space Division, is now a more up-to-date source. It attempts to survey all military satcom requirements and the technologies needed to achieve them. It surveys development programs and makes explicit recommendations. Because of the breadth of this study it rarely addresses MMICs explicitly. However, MMIC applications can often be inferred from the information in the report.

TABLE 2-1

PRIMARY WRITTEN REPORTS USED IN SURVEY

- Advanced Space Communications Technology Roadmap (Air Force Space Division/CGX, May, 1986)(3)
- Advanced Space Communications Technology Assessment (Prepared for Air Force STC and SD by The Aerospace Corporation, September, 1987)(4)
- Leadership and America's Future in Space, A Report to the Administrator by Dr. Sally K. Ride, August, 1987. (5)
- World Space Industry Survey- 10 Year Outlook (Euroconsult, November, 1986)(6)
- EIA Space Electronics Market Study (Fall, 1987)(7)
- An Assessment of the Status and Trends in Satellite Communications 1986-2000 (NASA Technical Memorandum 88867 by William A. Poley et al, Lewis Research Center, November, 1986)(2)
- The Telecommunications and Data Acquisition Progress Report 42-88 E. C. Posner, Editor (NASA, Jet Propulsion Laboratory, February, 1987) (8)
- The Military Satellite Communications Market in the U.S. (Frost and Sullivan, Inc., January, 1984) (9)
- ITU WARC ORB '85 (Report of the Advisory Committee for the ITU's WARC On the Use of the Geostationary-satellite Orbit and the Planning of Space Communication Services Using It, December, 1983)(10)
- Future Communications Satellite System Architecture Concepts (Final Report for Task Order 3, Prepared by Ford Aerospace and Communications Corporation for NASA, Lewis Research Center, November, 1987)(11)

TABLE 2-2

INDIVIDUALS INTERVIEWED FOR SURVEY
(Outside of Ford Aerospace Corp.)

- Air Force Space Technology Center (Capts. R. Kropf and R. Young and Lt. J. Abreu)
- Aerospace Corporation (L. Yuan, W. Bloss, B. Yamoda)
- Defense Communications Agency (Lt. Col. Ondo)
- Defense Communications Engineering Center (R. Williams)
- NASA Headquarters (R. Arnold, G. Knauss)
- Jet Propulsion Laboratory (Dr. L. Riley, A. Kermode, E. Caro, Dr. Fuk Li)
- Johnson Space Center (D. Arndt, B. Roberts)

The Frost and Sullivan and EIA studies are most valuable in providing information on status and timing of planned programs.

The Telecommunications and Data Acquisition Process Report 42-88 from JPL has several valuable papers on the use of 32 GHz for the downlink from deep space missions, on the benefits of 32 GHz, and on the solid-state millimeter wavelength circuitry which will be required to make this a reality. In particular the following papers in this volume are useful:

- Ka-Band Downlink Capability for Deep Space Communications by J. G. Smith(12)
- Ka-Band (32 GHz) Allocations for Deep Space by N. F. deGroot(13)
- Ka-Band (32 GHz) Benefits to Planned Missions by D. M. Hansen and A. J. Kliore(14)
- A Growth Path for Deep Space Communications by J. W. Layland and J. G. Smith (15)
- A Ka-Band (32 GHz) Beacon Link Experiment (KABLE) With Mars Observer by A. L. Riley, D. M. Hansen, A. Mileant, and R. W. Hartop (16)
- Ka-Band (32 GHz) Spacecraft Development Plan by A. L. Riley (17)

2.3 MILITARY REQUIREMENTS

The Advanced Space Communications Technology Assessment(4), prepared by the Aerospace Corporation, provides a comprehensive and up-to-date overview of perceived technology requirements for military space communications. The report considers all relevant technologies, so of necessity does not generally penetrate to the level of detail of indicating MMIC requirements explicitly. However, the general issues addressed by the report together with an understanding of the available techniques for implementing space communication hardware can identify areas where MMICs can play an important role.

According to that report(4) and interviews with individuals intimately involved with military space communications, the important technical issues in military space communications are:

- The need for greater bandwidth for antijamming and greater throughput.
- Improved survivability.
- Autonomy.
- Affordability
- The increased use of higher frequencies(44/20 GHz and eventually 94/100 GHz) to reduce congestion.
- The use of modular components (standard data buses and standard spacecraft modules) for lower cost.
- Maintaining long term utility of UHF networks.
- On-board processing.
- The use of superconducting materials.

The Aerospace Corporation report(4) attempted to summarize technology requirements for future military communication satellites by generating four composite MILSATCOM concepts which together embodied the communication system needs. These four conceptual systems and their general attributes are:

I. Evolutionary Narrowband
   20/44 GHz Space-Terminal Link
   100 Kbps -10 Mbps 60 GHz Crosslinks
   Dynamically reconfigurable interconnection management
   10 X 10 input-output switch matrix control
   7-year on-orbit satellite life

II. Evolutionary Wideband
   7/8 GHz and/or 20/44 GHz space-terminal link
   100 Kbps-100 Mbps 60 GHz Crosslinks
   Dynamically reconfigurable interconnection management
   4 X 4 input-output switch matrix control
   7-year on-orbit satellite life

III. Advanced Narrowband
   Cost effective utilization of evolutionary system technology base
   20/44 GHz, 94/100 GHz and/or laser space-terminal link
   100 Mbps - 10 Gbps laser crosslinks
   Real-time interconnection reconfigurability with priority message handling
   50 X 50 input-output switch matrix control

IV. Advanced Wideband
   Cost effective utilization of evolutionary system technology base
   20/44 GHz, 94/100 GHz and/or laser space-terminal link
   100 Mbps- 5 Gbps laser crosslinks
   Real-time interconnection reconfigurability with priority message handling
   20 X 20 input-output switch matrix control

As a result of considering these future concepts the study identified the technology drivers listed in Table 2-3.

TABLE 2-3

MILSATCOM TECHNOLOGY DRIVERS
(From the Advanced Space Communications Technology Assessment)(4)

- 44/20 GHZ SPACECRAFT-TERMINAL INTERFACE
  - 44/20 GHz Link Margin
  - 44 GHz Multibeam antennas
  - 44 GHz Low Noise Receivers
  - 20 GHz Power Amplifiers (10-30 Watt SSPA, 50 Watt TWTA)
  - Jamming and Scintillation Protection

- 60 GHZ CROSSLINKS
  - 5-10 Watt Solid State Power Amplifier (SSPA)
  - 100-300 Watt Traveling Wave Tube Amplifiers (TWTA)
  - 60 GHz Phased Array Transmit/Receive Antennas
  - 60 GHz Low Noise Amplifiers
  - Jamming and Scintillation Protection

- LASER CROSSLINKS
  - Acquisition, Pointing and Tracking
  - High Power Transmitter Diodes
  - High Speed Modulators
  - More Efficient, Lower Noise Detectors

- SPACECRAFT ELEMENTS
  - Hardened Components
  - Precision, Low Weight Frequency Synthesizers
  - High Speed Signal Processing Components
  - Advanced Interconnection Circuitry
  - On-orbit Self Test and Anomaly Resolution

- SUPPORTIVE TECHNOLOGIES
  - Reproducible, Limited Quantity Production of Components
  - Standardized, Space Qualified Components
  - Minimization of Size, Weight, Power, Complexity, Costs
  - Affordable Reliability, Survivability, and Autonomy Improvements
  - Protection Against Foreign Sole Source Components

- BREAKTHROUGH TECHNOLOGIES
  - 94/100 GHz and/or Laser Space-Terminal Interfaces
  - Rapid Beam Steering Laser
  - Superconductivity
  - Photonics
  - Fail Soft, Fault Tolerant Electronics
  - Wafer Level Union of Devices
  - Acoustic Charge Transport
  - Nonlinear Optics

As will be considered in more detail later in this report, many of these technology drivers relate directly to MMIC technology. In particular the requirements for multibeam antennas and phased arrays at 44 and 60 GHz lead to challenging, somewhat beyond the state-of-the-art requirements for MMICs. MMIC technology is key to making such systems practical. The technology may be applicable to the SSPAs at 20 and 60 GHz, to the 60 GHz low noise receivers, to the low weight frequency synthesizers, to the switch matrices, and, clearly, to the general needs for radiation hardening, and for minimization of size, weight, and cost.

The Strategic Defense Initiative (SDI) has extensive requirements for millimeter wavelength multibeam antennas with electronic scanning and nulling capability. Various architectures which are being considered for such a defense system depend on numerous 44 GHz ground-to-space links, 20 GHz space-to-ground links, and 60 GHz space-to-space links among the many geostationary and low earth orbit surveillance systems, battle managers, and weapon systems. In addition SDI has important needs for 60 GHz power amplifiers (10 Watts), 60 GHz low noise amplifiers, and frequency hopped synthesizers which could have some MMIC applicability.

Table 2-4 lists specific major upcoming military satellite programs and their present status, based largely on the EIA Space Electronics Market Study, Fall, 1987 (7)

TABLE 2-4

IDENTIFIED UPCOMING MILITARY SATELLITE PROGRAMS

DSCS III C	R&D Beginning 1988
DMSP BLOCK 6	RFP Expected FY 1989
GPS BLOCK 11R	RFP Expected 1988
BSTS	In Development
SSTS	Requirements Study Underway
SLCSAT	In R&D
LIGHTSAT	New Start in 1988
UHF FOLLOW ON	To Replace FLTSAT
DSP	Follow On Expected
SBR	Now in Concept Development

DSCS IIIC (Defense Communication Satellite System) is the planned upgrade of the current DSCSIII. DMSP Block 6 is a new version of the Defense Meteorological Satellite to improve reliability, utilize new launch vehicles and reduce mission costs. GPS Block 6 is a new version of the Global Positioning System to have increased life, less weight, crosslinks, radiation hardening, and 180 day autonomy. BSTS is the Boost Surveillance and Tracking System, in Phase III development from FY 87 to FY 89. SSTS is the Space Surveillance and Tracking System for which a requirements study is underway. The Submarine Laser Communications Satellite (SLCSAT) is presently an R&D effort. LIGHTSAT is a DARPA R&D effort to provide low cost short term communications for

tactical commanders The UHF Follow-on is to provide a replacement for FLTSAT and LEASAT with an emphasis on lower cost. DSP is the Defense Support System for which a follow on is expected but for which the details are classified. The Space Based Radar (SBR) for wide area surveillance is now in a concept development phase with start of full scale development anticipated in late 1989 or 1990.

It is clear that many of these upcoming military satellites will utilize 20 and 44 GHz uplinks and downlinks and 60 GHz crosslinks, with a need for electronic beam steering and antijam nulling. Therefore, they will have a critical need for MMIC transmit and receive active array modules. In addition, our studies indicate that monolithic technology can have an important application in the DSCS III C X-Band antijam antenna. This is described in detail in the following section of this report.

No detailed study was made of specific applications of MMICs in these other military satellite programs because the decision was made to concentrate this program on applications for NASA missions. However, from the MILSATCOM technology drivers listed in Table 2-3, it is clear that MMICs must play a critical role in future military satellites. In particular, the following are clearly possible applications of MMICs to address the technology drivers of Table 2-3.

- Active array modules for receiver arrays at 44 GHz to implement scanning multibeam and antijam systems.
- Active array modules for transmitter arrays at around 20 GHz.
- Active array modules for both receivers and transmitters at 60 GHz.
- Low weight frequency synthesizers.
- Components for on-board signal processing such as bulk demodulators and switch matrices.
- Reduction of size and weight of conventional transponder components to reduce cost and improve radiation hardening

2.4 COMMERCIAL COMMUNICATION SATELLITES

Communication satellites represent the largest market for space applications. This area has experienced rapid growth since the early 1970's. But because of the many factors discussed briefly in Section 1.4, this market is changing rapidly and all forecasts are subject to a great deal of uncertainty.

Figure 2-1, based on data from EUROCONSULT(6) shows the growth in number of communication satellite transponders. In 1986 almost 600 transponders were available for domestic United States communications, using the conventional 36 MHz transponder as a convenient measure of communication capacity. Of these, over one-third, approximately 230, were being used for video trans- mission for cable TV and for the TV networks(2). Approximately 60 were used for public switched networks, 50 for private voice communications and 25 for private data. As seen

from Figure 2-1, Euroconsult projects an increase in the number of transponders for domestic U. S. use to around 1000 by 1990.

An important consideration is that the possible number of transponders can not increase indefinitely since it is subject to technological limits. For instance for use for domestic U. S. communication, the satellite must be located within a portion of the geostationary arc encompassing about 88 degrees for C-Band transponders, 78 degrees for Ku-Band, and 20 degrees for Ka-Band. The number of transponders which can be placed within this arc is limited by the bandwidth made available for this service and the satellite spacing which can be used without interference between the satellites. Earlier systems required a minimum spacing of 4 degrees at C-Band and 3 degrees at Ku-Band. Technological advances have made it possible to decrease this spacing, so that newer systems will use 2 degree spacing. After setting aside some possible satellite sites for Canada and Mexico, the result is a possible 34 sites for C-Band transponders and 33 for Ku-Band transponders for domestic U. S. communications. (2)

The present state-of-the-art uses dual-polarized antennas by means of which each C-Band or Ku-Band site can accommodate 24 transponders (twelve 36 MHz transponders of each polarization). Thus, with 67 total C-Band and Ku-Band sites and 24 transponders per site, there is a potential for 1608 transponders for domestic U. S. communication using present technology.

To go beyond this 1608 transponder limitation requires a technological advance which can take any of a number of forms. One approach is the use of Ka-Band to open up additional spectrum. Another is to achieve additional frequency reuse (beyond the 2:1 reuse achieved through dual-polarization) by means of spot beams. Still another approach is to use advanced modulation and signal compression techniques which make more efficient use of bandwidth.
Any of these technological approaches to increasing capacity beyond that presently attainable, can be facilitated by the use of monolithic technology. A question which must be addressed, however, is how great is the need to expand the capacity beyond the 1608 transponder limit?

Several studies have been performed for NASA forecasting future demand for communication satellites. In 1979 the results of two NASA-sponsored studies were published. The studies were made by Western Union Telegraph Company and the U. S. Telephone and Telegraph Corporation, a subsidiary of International Telephone and Telegraph Corporation, and forecasted the domestic demand for telecommunication services to the year 2000. They also identified that portion of the demand that could best be served by satellite.

These forecasts were reassessed in 1983 by the same organizations, and in 1984 NASA published a synthesis of these reports incorporating new information (18). These results are summarized in Table 2-5.

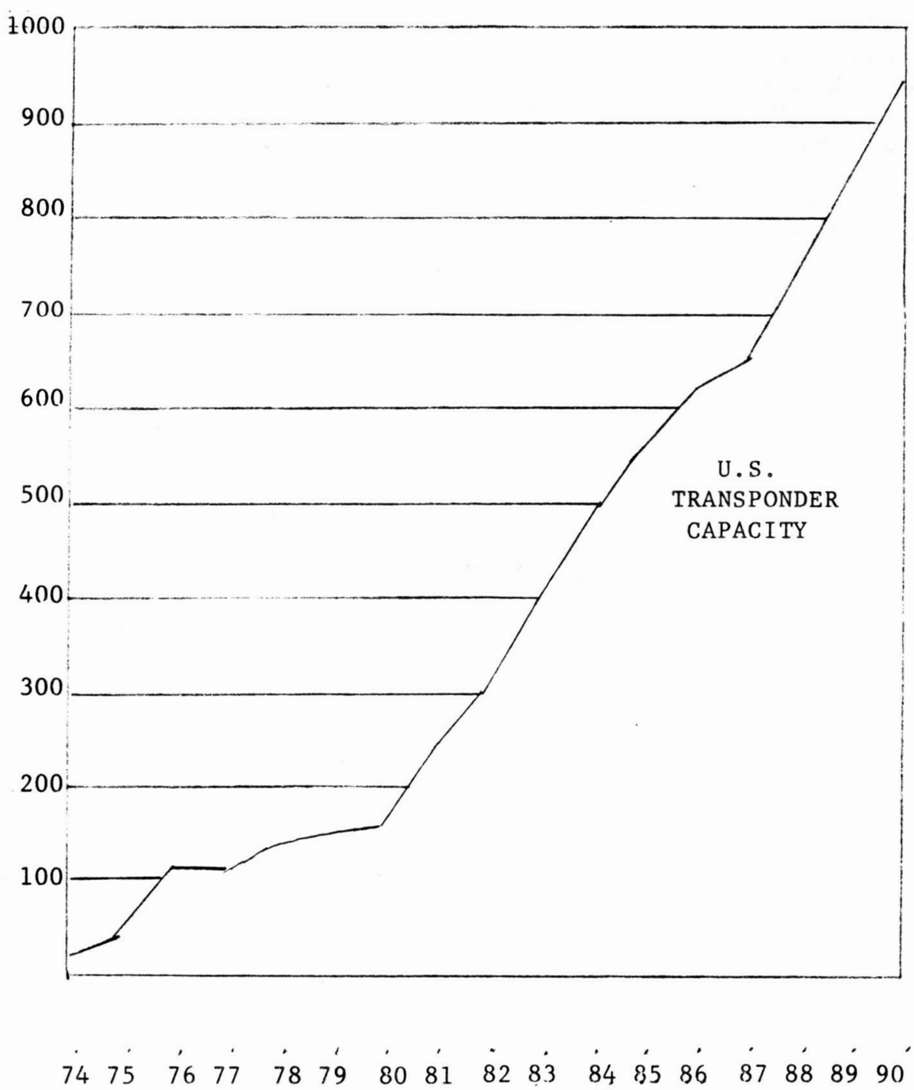


FIGURE 2-1 U.S. Domestic Transponder Capacity as a Function of Time

TABLE 2-5

Projected Satellite Addressable Demand (2)
(Equivalent 36 MHz Transponders)

	1989	1990	2000
ITT	360	1370	3600
WU	273	1140	2800
NASA	400	1150	2450

As can be seen these studies lead to the conclusion that, with present technology and the present frequency bands, the geostationary arc will be saturated for domestic U. S. communication in the early 1990's. This is the conclusion even of the NASA report which takes in to account some more recent trends which decrease projected demand.

As discussed in Section 1.4 the satellite communication business is changing rapidly under the influence of several factors such as:

- The rapid development of fiber optic cable as a long distance communication medium.
- The introduction of the Integrated Services Digital Network (ISDN).
- The use of Very Small Aperture Terminals (VSATs) to provide long distance service directly to the user, bypassing the terrestrial network.
- The recent launch problems which have increased the costs and uncertainties of satellite communications.
- The deregulation of the communication industry.

All of these factors have a major influence on requirements for communication satellites, and in many cases their influence is in opposite directions.

The rapid implementation of fiber optic cables has drastically lowered the present and projected use of satellites for long distance point-to-point trunking. However, the long haul portion is only a small part of the cost to the user of user-to-user service. The cost of the local network can be the major part of the overall cost to the user. This is the major incentive for the use of VSATs to provide service directly to the user, avoiding the cost of the local network. This service has grown rapidly and has become a significant user of communication satellites. However, to date this service has been restricted primarily to data transmission, since the systems presently utilize a double hop through a master station. The resulting time delay is not acceptable for voice traffic.

Satellites are very attractive for broadcasting large amounts of information from a central source to many destinations, as in the distribution of television programs. This is reflected in the fact

that approximately 230 transponders are presently being used for video transmission in the U. S. This use of satellites is expected to continue, but in the U. S. probably does not represent a growth market.

Satellites may provide the means of introducing ISDN service to many parts of the world. The wideband access will greatly increase the bandwidth per user.

Therefore, the projections such as those of Table 2-5 must be viewed with some skepticism and the recognition that the situation is very uncertain due to the many conflicting influences. The growth of the use of VSATs for customer premises service tends to offset the loss of satellite business to fiber optics. It is possible that the increase in use of VSATs for customer premises service will approximately offset the decline in satellite usage for long distance trunking, so that the projections of Table 2-5 will be approximately correct, with saturation of the geostationary arc for North America occurring in the early 1990's. This would be particularly likely if the use of VSATs to provide terrestrial bypass for voice communication becomes widespread. In this case normal growth would lead to demand significantly exceeding arc capacity in the early 2000's unless developments such as greater frequency reuse are implemented.

The use of VSATs for voice traffic seems to hinge on the elimination of the second hop and its attendant delay. This can be done if the satellite can be made to accomplish the function now served by the master ground station. This requires adding considerable complexity to the satellite with a resulting increase in size and weight which is probably prohibitive unless the maximum use is made of monolithic circuits. In particular, several studies (2,11) have identified bulk demodulators as a key technology for this application, as well as switch matrices.

The use of VSATs for voice communication and the development of satellites to accommodate them could be seen as the first step toward truly personal communication as an extension of cellular land mobile technology. Such concepts have been proposed(2) and their implementation would require advanced bulk demodulator capability, extensive frequency reuse through the use of large numbers of spot beams, and very large switch matrices. Monolithic technology would be the key to all of these needs.

Therefore, it is concluded that in the commercial satellite area, the candidate applications of MMICs, to be studied in more detail in the subsequent sections of this report, are the following:

- Modules for active transmitter and receiver arrays to implement scanning spot beams for frequency reuse in order to increase the capacity of the geostationary arc.
- Modules for active arrays at Ka-Band to open up additional spectrum.

- Bulk Demodulators to facilitate the use of satellites for two-way voice communication between VSATs.
- Switch matrices to enable frequency reuse and single hop voice communications.
- Use of MMICs to reduce the size and weight of conventional transponders, thus making them more economical.

2.5 APPLICATIONS IN NASA SPACE MISSIONS

NASA requirements tend to be mission driven and cover an extremely wide variety of applications. A broad overview of possible future NASA missions can be obtained from the "Ride Report" (5). The report describes four candidate initiatives, proposed as a basis for discussion in defining goals and objectives for the space program. Although it is not anticipated that all four initiatives will be pursued in their entirety or in the form proposed in the report, the proposed initiatives illustrate the range of possibilities for future NASA missions and give some idea of the technologies which will be required.

The four initiatives described by the report are: (1) Mission to Planet Earth, (2) Exploration of the Solar System, (3) Outpost on the Moon, and (4) Humans to Mars.

To identify areas where MMIC technology can contribute to future NASA missions, discussions were held with NASA technical personnel involved in studies for projects related to these four initiatives. In addition, discussions were also held with individuals familiar with the requirements for systems, such as TDRSS and the Space Station, which will provide necessary support for these initiatives as well as other possible space missions.

In particular discussions were held with the following individuals at the Jet Propulsion Laboratory of the California Institute of Technology:

- Dr. Lance Riley (Deep Space Missions)
- Arthur Kermode (Spacecraft Transponders)
- Ed Caro (Synthetic Aperture Radar, Mission to Planet Earth)
- Dr. Fuk Li (Radar)

JPL reports provided by these individuals were helpful in identifying requirements. D. Arndt of the Johnson Space Flight Center provided useful information regarding the Space Station. Barney Roberts of Johnson was interviewed regarding Lunar Bases. At Ford Aerospace many individuals contributed information regarding the Space Station and TDRSS.

The general requirements of these missions and projects as they possibly relate to MMICs are described in the following paragraphs.

2.5.1 DEEP SPACE MISSIONS

A major factor in determining the technology required to support future deep space missions is the planned move from X-Band to Ka-Band (32 GHz). The decision to use Ka-Band was made after extensive study demonstrated its advantages, at least until some future time when optical links may become a superior approach.(12, 13)

The advantage of Ka-Band is basically the higher antenna gain which can be achieved for the same antenna dimensions. The potential improvement in going from 8.4 GHz to 32 GHz is 11.6 dB due to the increased antenna gain. This is offset somewhat by atmospheric effects and actual antenna performance, but an improvement of at least 8 dB has been established. This 8 dB advantage can be exploited in various ways depending on the mission needs.(14) For example, for the same antenna size and data rate, the power can be reduced for missions where power is at a premium. Since DC power is typically obtained from a radio isotope thermonuclear generator (RTG), at a cost of $200,000 per Watt, this can be an important driver. On the other hand, in some situations it may be more desirable to use the 8 dB advantage to reduce antenna size, or to increase the data rate with the same antenna size and power consumption. (14)

Some planned planetary missions which will use the new Ka-Band capability are the Comet Rendezvous Asteroid Flyby (CRAF), Cassini (Saturn Orbiter/ Titan Probe), Mars Sample Rover (MSR), and Neptune Orbiter Probe. In addition, as part of the development path to this capability a Ka-Band link experiment is planned for the Mars Observer. The deep space programs are summarized in Table 2-6, and described in more detail later in this report.

2.5.2 TRANSPONDERS

As in conventional communication satellites, transponders for use in space missions consist of a receiver, frequency converter, and transmitter. For example, an uplink X-Band signal is received, amplified, and downconverted to baseband, then upconverted to drive the transmitter at a K-Band downlink frequency. Also as in the case of communication satellite transponders, it would be possible to make very substantial reductions in the size and weight of the transponder through the use of MMICs. However, since the quantities involved are very small, use of MMICs will probably be limited to generic, "off-the-shelf" chips unless techniques are perfected to make custom MMICs affordable for small quantity applications.

TABLE 2-6

Ka-Band Requirements for JPL Deep Space Missions

Mission	Year(approx)	Description
Mars Observer (MOS)	1990	Transmission experiment. Ka/X-Band antenna using sub and primary reflector dish antenna.
Comet Rendezvous Asteroid Flyby (CRAF)	1991-2	Ka-Band amplifier. One candidate is to use a MMIC power amplifier.
Cassini (Saturn Orbiter)	1996	Ka-Band phase shifter/power amplifier antenna feed array modules with dish antenna.
Mars Sample Return (MSR)	2000	Ka-Band amplifier array with more elements and a plane antenna of patch radiation elements.

2.5.3 RADAR SYSTEMS (MISSION TO PLANET EARTH)

Radar development is taking place at JPL for synthetic aperture radar (SAR) which was first demonstrated by JPL in 1978 in SEASAT. The next JPL SAR was demonstrated as Shuttle Imaging Radar A, (SIRA), in 1981 and as SIRB in 1984. The next SAR will probably be on the Venus radar mapping mission, Magellan, scheduled for a shuttle launch. The Earth Orbiting Satellite (EOS) series, as part of Mission to Planet Earth, will map the earth surface using SAR. SAR missions and systems are summarized in Table 2-7.

TABLE 2-7

SAR Missions and Systems
SEASAT - 1978
SIRA - 1981
SIRB - 1984
MAGELLAN
SIRC - 1992
NASA SCATTERMETIC (NSCAT) - 1993
EOS1 - 1994
EOS2 - 1995
SPACE STATION (Altimeters)
TITAN (Saturn Moon Mapper) - 2000

MMICs appear to have the potential for benefitting at least some of these future radars quite significantly. As phased array radars they require a large number of active elements; and as space systems, size, weight, and reliability are crucial considerations.

The potential synthetic aperture radar application of MMICs will be considered in detail later in this report.

2.5.4 TRACKING AND DATA RELAY SATELLITE SYSTEM

The experimental and scientific satellites launched and operated by NASA generate large amounts of data which must be returned to earth. The transmission of this data has long been dependent on NASA's world wide network of Satellite Tracking and Data Stations. Data is stored on board the satellite until it is in view of one of the stations, at which time it is dumped to the earth. This network is expensive to maintain, and depends on stations in foreign countries where political considerations may cause complications.

For some time it has been NASA's goal to replace this network with the Tracking and Data Relay Satellite System (TDRSS). By means of this system, the scientific and experimental satellites will transmit their data to the TDRS which will relay the data to a single ground station at White Sands. This will alleviate many of the problems with the present system, reduce the requirements for storing data on board the spacecraft, and increase the amount of data which can be returned.

Problems such as the shuttle disaster which destroyed the second TDRS have plagued the program and delayed its operation, but the need for it continues to exist and will grow more acute as space activities increase. Hence, NASA is considering improvements to TDRS. In addition, planned and projected missions in the 2000-2015 time frame, such as an expanded Space Station, polar and co-orbiting platforms, orbiting transfer vehicles and low-earth orbiting missions will require an Advanced Tracking and Data Relay Satellite System (ATDRSS) to meet NASA's mission requirements. The Advanced TDRSS will maintain existing TDRSS services at S- and Ku-Bands and will add new 60 GHz and laser space-to-space links. Multiple space-to-ground links at Ku- and/or Ka-Bands will also be added.

Improved versions of TDRS and the longer range ATDRS appear to have several possible applications of MMICs. ATDRS has a tentative requirement for multiple beam communications antennas with five fixed and one movable beam covering CONUS, and one world-wide mobile movable beam operating in the Ku- and Ka-Bands. These requirements are summarized in Table 2-8.

TABLE 2-8
Summary of Tentative ATDRS Antenna Requirements

Communication Use	Transmit	Receive	Transmit	Receive
Frequencies (GHz)	13.80	14.98	19.45	29.25
Bandwidth (GHz)	0.80	0.75	4.0	4.0
Diameter (meters)	-------------------2.0-------------------			
Gain (dB)	46.2	46.9	49.2	52.7
Beamwidth (degrees)	0.69	0.65	0.50	0.33
Fixed Beams*	---------------6 for CONUS---------------			
Movable Beams*	---1 for CONUS--------		1 for World Wide--	

* Some beams may use only one of the frequency bands while others may use both. Beam frequency allotments are open at this time. An MMIC based active array can be considered for this requirement.

Another possible TDRS application was also identified. This application is in the S-Band space-to-space links in an improved implementation which would provide on-board beam forming to replace the ground based processing required by the present TDRS. On-board beam forming has the advantage of eliminating the need for transmitting the signals picked up by the thirty antenna elements to ground for processing. This would free up spectrum space for other uses, facilitate future upgrades to more beams or antenna elements, and eliminate problems caused in the present approach by differential phase shifts in the space-to-ground link.

2.5.5 SPACE STATION

The Space Station has specialized communications requirements which will likely require MMICs for their realization. The requirements can be divided in to two categories: communication services to nearby (within 37 km) vehicles and activities (the so-called control zone), and the far range communication to satellites in the 37 km to 2000 km range. The services to spacecraft in the control zone include the capability to distribute audio, video, telemetry, command and heads-up display data to/from free flyers, National Space Transportation (NSTS), Orbiting Maneuvering Vehicle (OMV), Extravehicular Activity (EVA) terminal, Mobile Service Center (MSC), and the Mobile Transporter (MT). The specific services to be provided to each user to and from the space station are given in Table 2-9, derived from JSC-31000.(19) A basic subsystem would support four simultaneous users subject to the requirements of Table 2-9. A proposed baseline design for Ku-Band provides seven 40 MHz wide channels in both the forward and reverse directions with one high data rate carrier (44 Mb/sec) or two low data rate carriers in each channel. It would use omni antennas for users in proximate zone, and two 2 ft. parabolas for communication to 37 km.

Several frequency bands are under consideration for these cluster communication operations. In January, 1987, NASA requested the NTIA for the use of the 14.0-14.3 and 14.5-14.89 GHz Bands for this service. NTIA recommended against this and recommending, instead, the consideration of the following bands in order of desirability:

a. 32-33 GHz (primary)
b. 21.4-22 GHz (possible primary)
c. 22.5-23.56 and 25.26-27.0 GHz (possible overflow bands)

Trade-off studies have been performed by GE Aerospace on the use of these bands.(19) As would be expected, the suitability of the higher frequency bands is highly dependent on the projected capability of solid state devices at these frequencies in terms of power output, efficiency, and noise figure. In particular, the attainable range in the EVA to space station return link is restricted by available DC power and RF power device efficiency. Some of the important assumptions used in the trade study were:

a. EVA transmitter power of 0.8 W @ 21 GHz, limited by projected 20% efficiency and available DC power.

b. EVA Transmitter power of 0.6 W @ 32 GHz, limited by projected 15% efficiency and available DC power.

c. Space Station transmitter power of 8 W for six devices at 21 GHz.

d. Space Station transmitter power of 5 W from eight to sixteen devices at 32 GHz.

e. Noise figures of 3 dB at 21 GHz and 3.3 dB at 32 GHz.

TABLE 2-9
SPACE STATION COMMUNICATION SERVICES

USER	COMMANDS	TELEMETRY	VOICE	VIDEO	TEXT/ GRAPHIC	DISTANCE (km)
Nominal Data Rate	LDR (Note 1)	LDR (Note 1)	LDR (Note 1)	HDR (Note3)	MDR (Note 2)	
Free Flyer	TO	FROM				37
NSTS			TO/FROM			37
OMV	TO	FROM		FROM		37
EVA Terminal		FROM	TO/FROM	FROM	TO	1
MSC	TO	FROM		TO/FROM		.2
MT	TO	FROM		FROM		.2

Note 1: LDR (Low Data Rate) is nominally 100kb/s comprising audio plus command/telemetry.
Note 2: MDR (Medium Data Rate) is nominally 500 kb/s comprising heads up display data plus audio plus commands.
Note 3: HDR (High Data Rate) is nominally 22 mb/s comprising video plus audio plus command/telemetry.

In the longer term, this baseline system using omni antennas for near-by users and dishes for more distant users will be inadequate. As the number of users increase, the number of dishes must increase at the expense of size and weight. An electronically steered multibeam antenna using MMIC active elements has many advantages in terms of size, weight, reliability, and flexibility.

2.5.6 SUMMARY OF POSSIBLE NASA APPLICATIONS

As a result of the information gathered on this survey, the possible NASA applications for MMICs to be considered are:

* Transmitter modules at 32 GHz for interplanetary missions.
* C-Band modules for synthetic aperture radar.
* Active array modules for multibeam antennas and on-board beam forming for ATDRS.
* Modules for electronically steered multibeam antenna for the Space Station.

3.0 POTENTIAL MMIC APPLICATIONS

The previous section discussed the results of the survey of future military, commercial, and NASA missions which might be benefitted by monolithic technology. The benefit could conceivably range from economies resulting from size and weight savings in some applications, to situations where the application is not possible or feasible at all unless MMICs realize their promise for producing complex microwave circuits in large quantities with a size that cannot be achieved in any other way. Section 2 surveyed possible applications using only general criteria to identify those applications which might benefit from, or require, MMIC technology. In this section the applications which were identified will be examined in more detail to identify the technical requirements so that the feasibility and/or necessity of the MMIC approach can be evaluated and compared with competing technologies.

The following applications will be considered:

- Use of MMICs in conventional communication satellite transponders.
- Use of MMICs as the active elements in active transmit and receive arrays to provide electronic beam steering and/or antijam nulling.
- Use of MMICs in deep space probes.
- Use of MMICs in the Space Station.
- Use of MMICs for on-board signal processing.

3.1 USE OF MMICS IN CONVENTIONAL TRANSPONDERS

The transponder in a conventional "bent-pipe" communication satellite consists essentially of a low noise amplifier at the uplink frequency, a converter to the downlink frequency, and a power amplifier at the downlink frequency to generate the transmitted signal. In addition a considerable number of filters is required to channelize the signals. The band is typically divided into 36 MHz channels each with its own power amplifier. There may be considerable additional complexity, for instance to provide switching for redundancy, or to make it possible to interconnect transponders at different frequencies.

A simplified block diagram of a typical transponder is shown in Figure 3-1. It can be seen that there is one receiver (consisting of a low noise amplifier, mixer and local oscillator) for each polarization and receive band. Each covers the full 500 MHz band. The down converted signals are then channelized into typically 36 MHz bands, amplified by a channel driver amplifier, and applied to the power amplifier, either a Solid State Power Amplifier (SSPA) or a Traveling Wave Tube Amplifier (TWTA).

Several observations can be made. First, the number of low noise amplifiers, local oscillators, and mixers is fairly small, basically two each (one for each polarization) for each uplink band (two uplink bands in this case). This number is usually then doubled to provide

redundant spares. On the other hand, the number of power amplifiers and channel drivers is considerably greater since one (plus some redundancy) is required for each 36 MHz channel.

Some general observations can also be made. Weight, as in all space applications is critical, so the use of MMICs to reduce weight has obvious appeal. Reliability is also critical, and also an argument for MMICs.

On the other hand, electrical performance specifications are normally quite difficult. Power amplifier efficiency and receiver noise figure is often required to approach the state-of-the-art, since these parameters affect overall system performance and, hence, the economics of the system.

In principle all of the microwave circuitry in a conventional bent pipe transponder is a candidate for replacement by MMICs. The low noise front ends and the power output stages of the transmitter SSPAs clearly present technological problems which will make them among the more difficult circuits to replace by MMICs. However, much of the intermediate power level circuitry is a near term possibility for MMIC. In particular the channel driver amplifier is a particularly promising candidate for MMIC implementation. Not only is it at an intermediate power level, but the same channel amplifier circuit is often used many times in a transponder. For instance, one modern transponder uses 29 channel amplifiers, so reducing the weight of each one can make a significant reduction in the weight of the overall satellite.

The channel driver amplifier accepts the signal from the input multiplexer and provides the amplification necessary to drive the output TWTA or SSPA. Importantly, the channel driver is generally required to provide commandable gain control. The block diagram of a current state-of-the-art channel driver is shown in Figure 3-2. This design uses dual-gate FETS to achieve electronically controllable gain by means of the voltage applied to the second gate. The dual-gate FETs are chip devices, so hermetically sealed modules are used. Six stages are used to achieve a minimum of 45 dB gain in the maximum gain state. The gain can be commanded to any of eight gain levels in three-dB steps. The control circuit switches in one of eight level set/temperature compensation circuits in accordance with an input command. The level set/temp comp circuits are resistor-thermistor circuits which provide the correct voltage as a function of temperature to the second gates to provide the desired gain over the operating temperature range.

The size of a current state-of-the-art channel driver for 12 GHz is approximately 24 cubic inches and it weighs 1.2 lbs. It uses a two layer construction with the RF circuitry on one level and the control circuitry and most of the DC circuitry on the other. Over half the volume is consumed by control and DC circuitry.

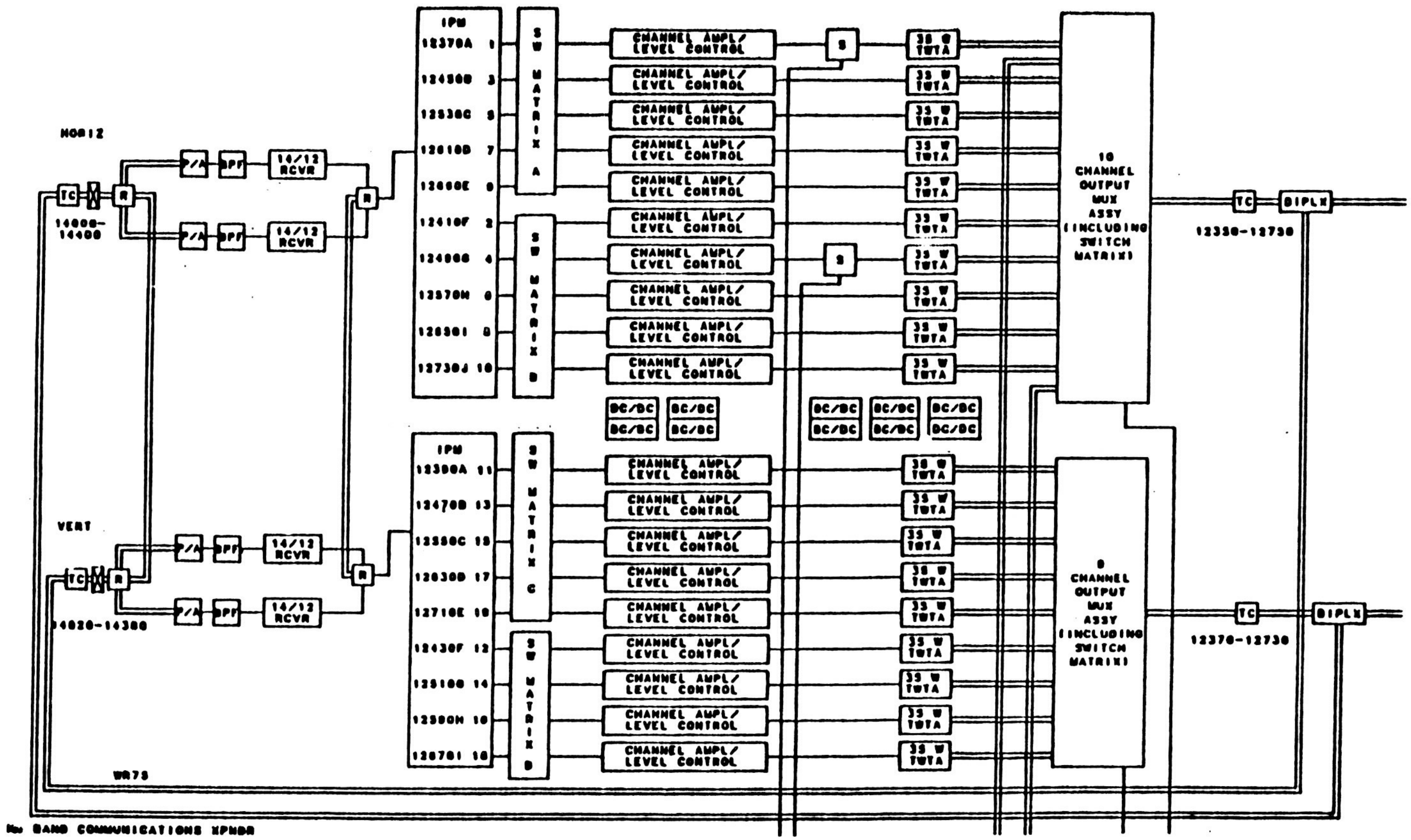


FIGURE 3-1 Simplified Block Diagram of a Typical Communication Satellite Transponder

The performance of this channel driver is satisfactory, but reduction of the size and weight would be very desirable.

One possibility for size and weight reduction is to use generic MMIC chips which have recently been introduced by some vendors. A possible implementation is shown in Figure 3-3. It uses broadband chip amplifiers, such as the Harris HMM-11810-0, 6-18 GHz amplifier, and chip variable attenuators, such as the M/ACOM MA4GM321, DC-20 GHz attenuator. Since the amplifiers are generic broadband units they only produce 4.5 dB gain per chip, so 12 chips are required. Nevertheless, the size of the RF portion of the circuitry is estimated to be only approximately 3" x 0.75" x 0.25", a considerable size reduction. A more subtle but equally significant benefit results from the characteristics of the MMIC Devices. The variable attenuators are temperature stabilized with the result that the control circuitry is greatly simplified. The gain control circuit only needs to provide a single value for each gain level independent of temperature. Two variable attenuators are used to achieve the 21 dB of gain variation. A third is used to compensate for the gain change of the amplifiers with temperature. A single resistor-thermistor circuit (instead of eight as in Figure 3-2) provides the voltage to this variable attenuator.

However, even greater size reduction and better efficiency could be achieved by using custom MMICs rather than the generic devices. This is shown in Figure 3-4. In this case the amplifiers are optimized for the downlink band of interest with the result that the required gain should be attainable with only about three amplifier chips. Instead of an analog variable attenuator, a three-bit digital attenuator is used. This incorporates on a single chip the FET switched attenuator circuit illustrated in Figure 3-5. The digital attenuator greatly simplifies the control circuit since the FETs are switched either hard on or off. It should be possible to make the attenuator inherently stable with temperature, so, here again it is only necessary to temperature compensate the amplifiers either through the bias circuit or, as shown here, with the analog attenuator.

A careful and realistic layout was made of each of the two MMIC realizations to compare with the present hybrid MIC approach. The results are shown in Table 3-1.

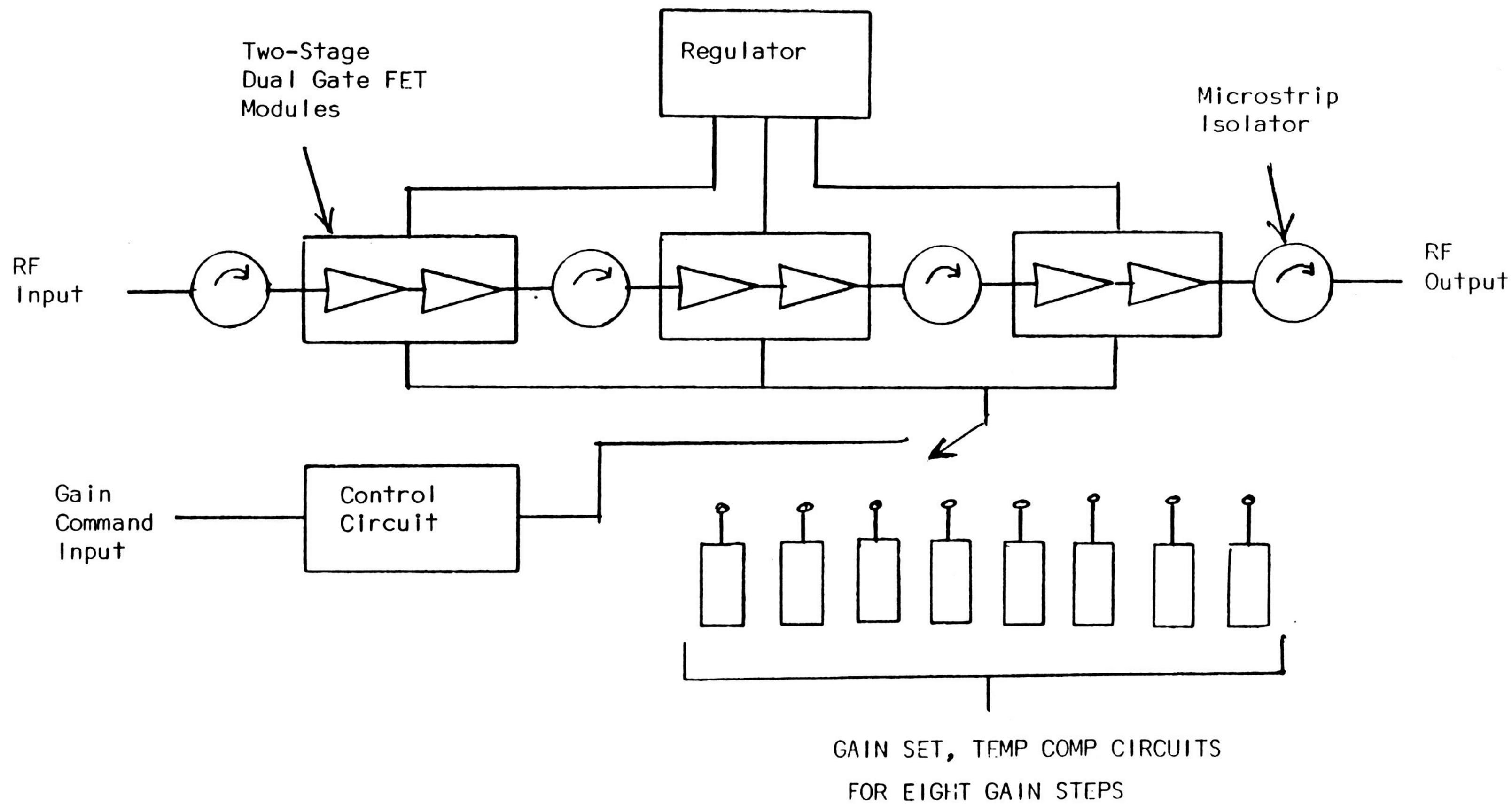


FIGURE 3-2 Block Diagram Of Current State-Of-The-Art Channel Driver Amplifier

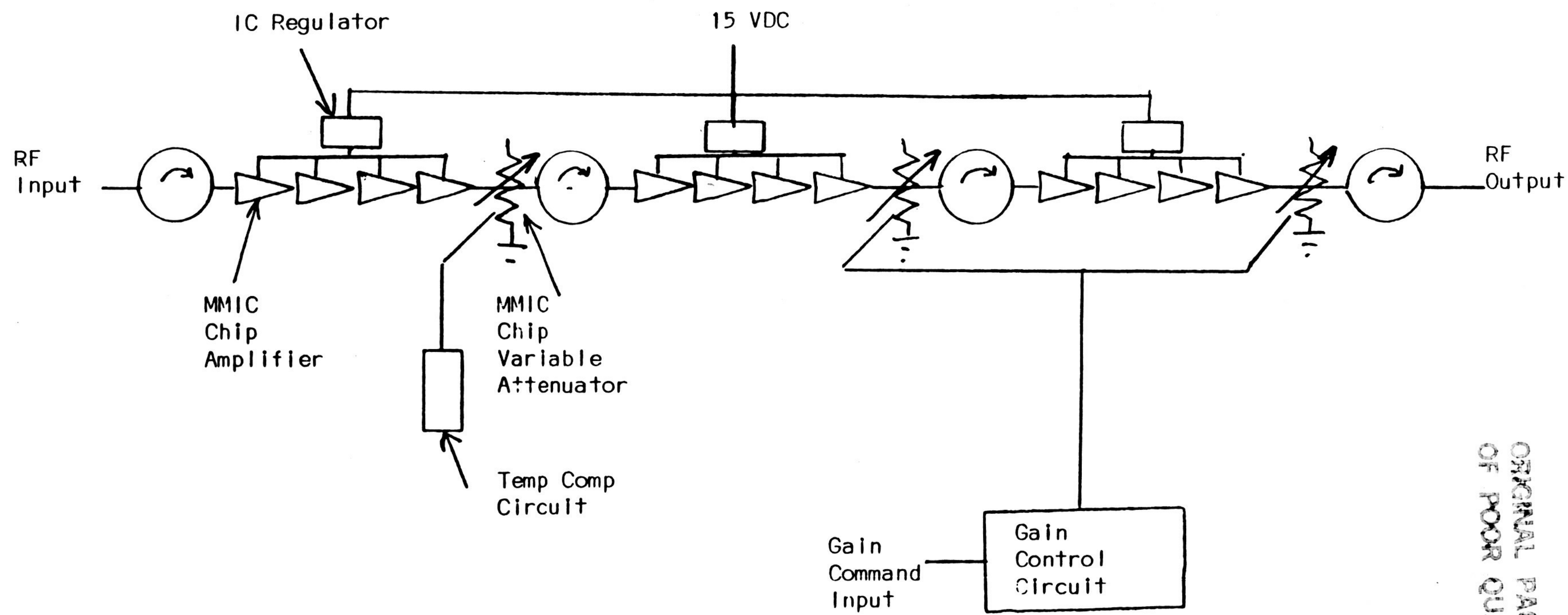


FIGURE 3-3 Channel Driver Using Generic MMICs

TABLE 3-1

SIZE AND WEIGHT

OF PRESENT AND PROPOSED CHANNEL DRIVERS

APPROACH	APPROXIMATE VOLUME	APPROXIMATE WEIGHT
(1) PRESENT HYBRID MIC	24 cubic inches	0.55 kg (1.2 lbs)
(2) GENERIC MMIC	14 cubic inches	0.27 kg (0.6 lbs)
(3) CUSTOM MMIC	8 cubic inches	0.16 kg (0.36 lbs)

Typical electrical requirements which would have to be met by such an MMIC channel driver are:

FREQUENCY: .... 12.25-12.75 GHZ
GAIN (in max gain setting)....... 45 dB
COMMANDABLE GAIN VARIATION....... 21 dB in 8 steps
NOISE FIGURE..................... 7 dB
OUTPUT (@ 1 dB compression)...... 10 dBm
GAIN STABILITY...................+/- 1 dB over -10 to +55 Centigrade

A typical modern transponder contains 29 of these channel drivers, so the overall size and weight savings is significant. With a reduction of 0.39 kg per channel amplifier and 29 amplifiers per spacecraft, the total weight savings is 11.3 kg. It is generally estimated that one kilogram of weight saving in a geostationary spacecraft results in a savings of $50,000. Thus, this 11.3 kg weight reduction should result in a savings of $560,000 per flight due to weight reduction alone. In addition the recurring cost of the MMIC version should be less than that of the hybrid version. Thus, it is estimated that the nonrecurring development cost could be recovered by the weight savings on the first satellite the amplifier is used on, with substantial savings on all subsequent flights.

It should also be quite feasible with present technology to replace the initial stages of amplification in a SSPA with an MMIC chip, resulting in a further weight reduction. This, too, has significant leverage because of the large number of power amplifiers. A typical C-Band SSPA weighs approximately 0.6 kg, excluding the DC/DC converter. A small portion of this could be replaced with present monolithic circuitry, however, significant reduction of this 0.6 kg would require realizing high power amplifier stages (for instance several Watts at C-Band) in monolithic form.

Most of the receiver circuitry could be realized with present MMIC technology, with the possible exception of the input stage where the lowest possible noise figure is desired. A typical flight C-Band receiver, including local oscillator, weighs about 1 kg. Since a typical satellite uses only four of these receivers, it is difficult to justify the development cost of custom MMICs.

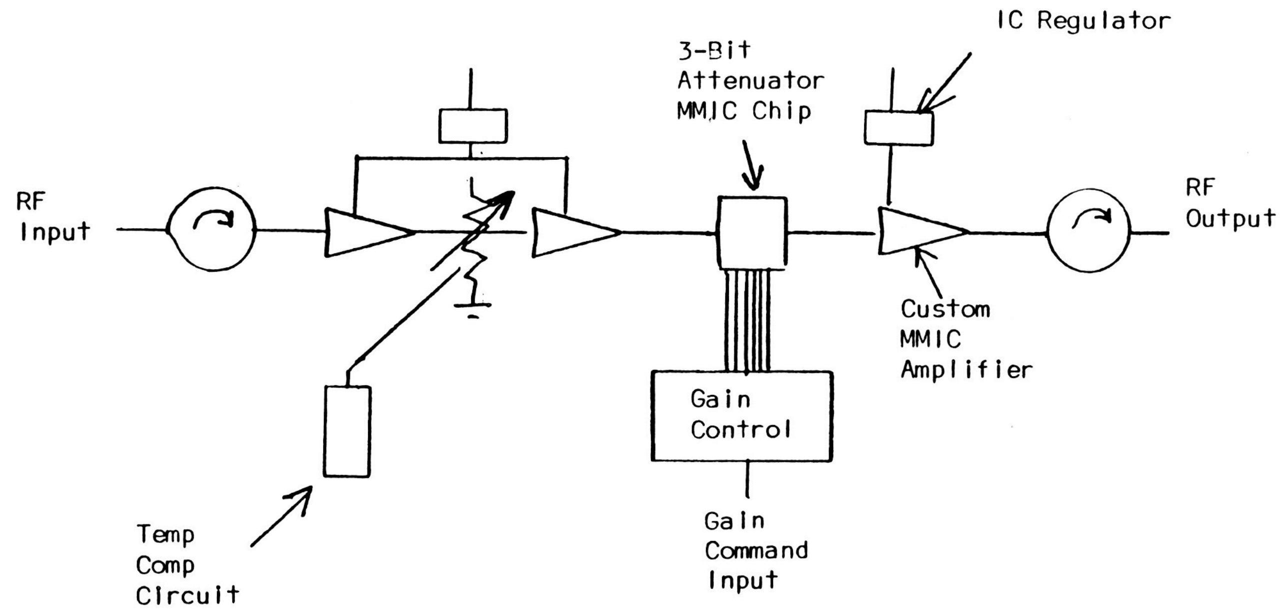


FIGURE 3-4 Channel Driver Using Custom MMICs

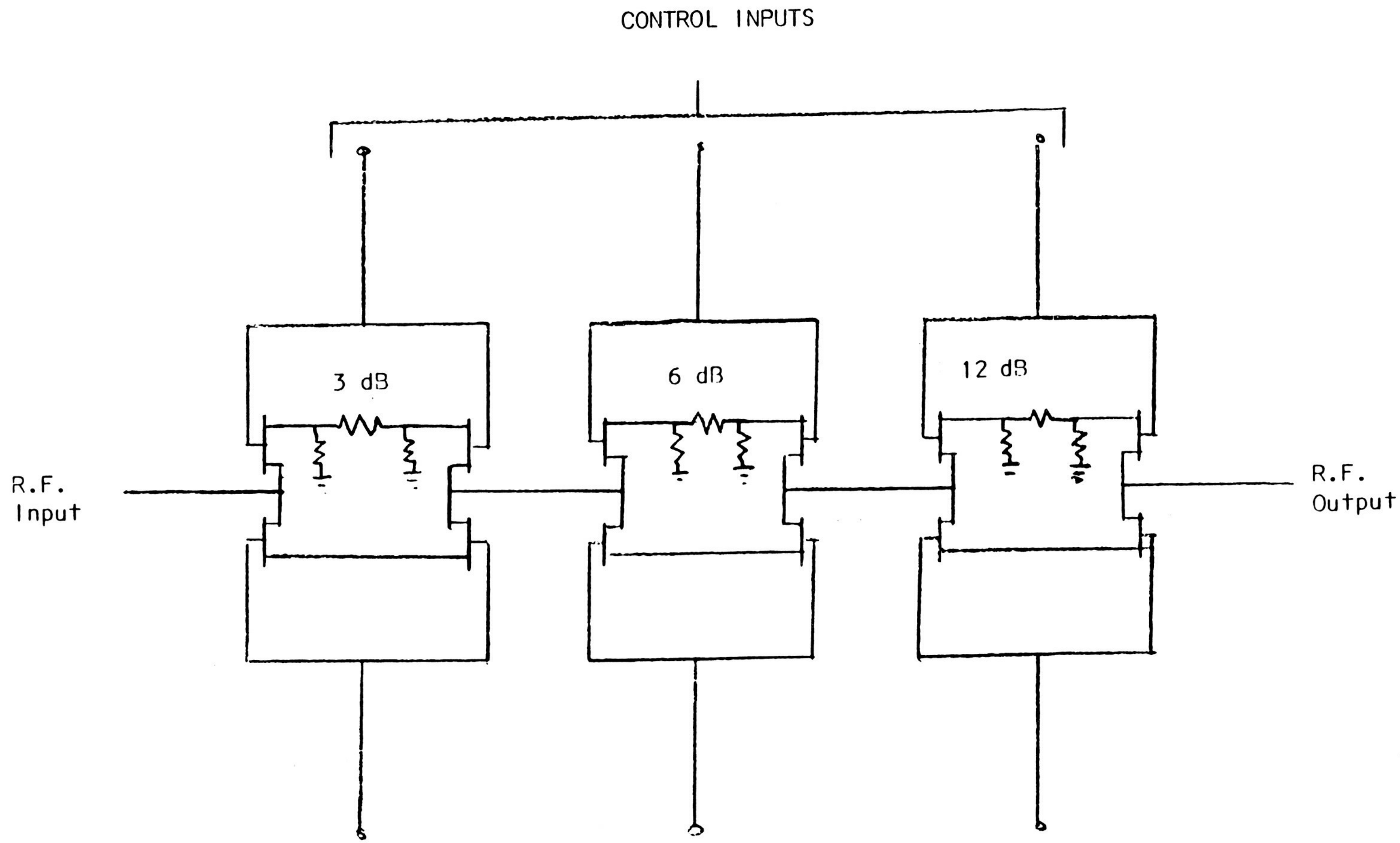


FIGURE 3-5 MMIC Switched Attenuator

However, as generic, "off-the-shelf" MMICs become available they will undoubtedly be utilized wherever possible to reduce the weight of the receiver and LO.

A significant amount of weight in a conventional transponder is consumed by filters. A typical, transponder has three types of filters:

a. High performance, narrow band for low power (input) applications

b. High performance, narrow band for high or medium power (output) applications

c. Miscellaneous, relatively wideband, low power filters

Because high quality, low loss filters for narrow bandwidths are very heavy using conventional techniques, such as silver plated invar cavities, a great deal of development has been devoted to more sophisticated approaches for satellite application with the result that filters for communication satellites are presently realized using three constructions:

a. Graphite fiber reinforced plastic
b. Thin wall invar
c. Dielectric resonator

Very little work has been done on active filters using MMIC techniques compared with the large amount of effort which has been devoted to more obvious applications of MMIC technology. However, in principle, it should be possible to use the inexpensive active devices offered by MMICs, to overcome the losses of low Q filter elements, as is done at lower frequencies. The large size and weight of high quality filters results from a seemingly inevitable tradeoff in passive circuits: as the size is reduced, circuit losses increase. If active devices can be used to overcome this loss, the very glossy but very small spiral inductors and MIM capacitors of MMIC circuits could be used to realize filters. Such techniques even if successful would be power limited and usable only for the low power filters of the satellite. But such low power filters account for about 7.5 kg in a typical communication satellite, representing about $375,000 per flight, using the $50,000 per kg estimate. Clearly this is significant. However, several important questions would have to be asked of any MMIC active filter realizations:

a. What performance is achievable?
   - Effective Q
   - Temperature stability
   - Power consumption
   - Out-of-band response
   - Reliability

b. Cost benefit tradeoff

c. Integrability and flexibility for use with MMIC front ends

The questions of power consumption and reliability are critical issues. Present passive filters, of course, cannot be surpassed in these areas. Active filters would have to have sufficient advantages in other areas to overcome whatever penalty they would have in these.

3.2 APPLICATIONS OF MMICS TO ACTIVE ARRAYS

Antenna arrays make possible the use of rapidly scanned narrow beams. The use of such electronically scanned, or switched, beams has many important system benefits. Spot beams permit frequency reuse to make optimum use of the limited frequency spectrum. Rapid electronics scanning can be used to implement time division multiple access (TDMA). Array antennas can also be used to null out interference or jamming in a communication system. In some applications, such as the Space Station or the Boost Surveillance and Tracking System, (BSTS) movable beams are required in order to track a moving spacecraft. Even in situations where, in principle, a gimballed, mechanically scanned antenna is adequate, an electronically scanned antenna offers reliability advantages by eliminating the complex moving parts. In addition, in some instances a significant advantage of an active array is its suitability for use with solid state power sources.
For the foreseeable future useful transmitter power levels will require the combination of the power from many solid state devices. Spatial combining by means of an array is an attractive means for combining the outputs of many solid states sources.

Active arrays represent one of the clearest space applications of MMICs. Such arrays will require large numbers of identical active circuits. These circuits must be small enough to meet the constraints imposed by the physics of the array. They must be economical if the system is to be cost effective. They must be highly repeatable from unit to unit so that the elements of the array will track each other over temperature and frequency. And, of course, like all components for space application, they must have assured reliability.

Conventional hybrid MIC modules are unsatisfactory in all of these respects, especially at the higher frequencies where most of the space requirements for active arrays exist. They are unrepeatable because the performance is so sensitive to mechanical tolerances which are unachievable in production. As a result they require much skilled technician time to tune them for the desired performance, and are, therefore, expensive. They are particularly difficult to tune so that they track well over frequency and temperature. Finally, the wire bonds of the hybrid MIC significantly degrade the reliability.
It is likely that millimeter-wavelength active arrays will be practical only if MMICs realize their promise of being able to produce large numbers of identical circuits at an economical price.

3.2.1 GENERAL CONSIDERATIONS FOR ACTIVE ARRAYS

An electronically scanned antenna can be implemented in many ways: for example, as a true phased array with radiating elements distributed over the full aperture and with means for controlling the phase of the individual elements; as a dual reflector antenna with a phased array feed; and as a dual reflector antenna with a focal plane array feed. Such different implementations place significantly different requirements on the phase and amplitude control characteristics for the individual radiating elements and, therefore, on the MMICs. In addition, in principle, the electronically scanned beam does not require active elements. That is, a transmitter array can be realized with a single high power amplifier, such as a TWTA, and power dividers, phase shifters and variable power dividers. Such an implementation suffers from loss between the radiating elements and the active devices which can seriously impair the efficiency of a transmitter or the noise figure of a receive system, but in some situations may be a practical system realization.

If an active array is required to meet the systems requirements, several candidate implementations exist and must be considered. For instance, a trade off between MMIC and hybrid MIC realizations for the active elements, and requirements such as the number of active elements and the required electrical performance must be considered in the trade.

Therefore, in order to define the requirements which must be met by MMICs for electronically scanned arrays, and to compare the MMIC approach with competing technologies, requires, at the minimum, consideration of the following system approaches:

1. Active Phased Array
2. Dual Reflector with Active Phase Array Feed
3. Dual Reflector with Active Focal Plane Array Feed

These approaches must be considered with both MMIC and hybrid MIC active elements, and they must be compared with mechanically scanned implementations and with implementations using passive arrays, (that is approaches using a single transmitter or receiver connected to power dividers and control elements). In addition the arrays can be configured in various ways. For instance, in a receiver array, the combination can be done at RF, or the active elements may incorporate mixers fed by coherent LOs in which case the combination is done at IF.

For the arrays the following characteristics of the elements are important and must determined to define the requirements for the MMICs:

RECEIVE ARRAYS

Frequency and Bandwidth
IF Frequency
Noise Figure
Gain
Gain Control (Amount of gain variation required and resolution of control)
Phase Shift Control (Amount of phase variation required, resolution, and required phase vs frequency characteristics)
Response Time of Gain and Phase Controls
Input and Output Impedances (VSWR)
Group Delay Variation
Variation of Phase with Gain Changes
Variation of Gain with Phase Changes
Means of Control (Method of sending control commands to the elements)
LO Requirements
Power Consumption

TRANSMITTER ARRAYS

Frequency and Bandwidth
Power Output
Gain
Gain Control (Amount of gain variation and resolution of control)
Efficiency as a Function of Gain and Power Output
Linearity Requirements (Intermod level and Phase Shift as a Function of Drive Level)
Phase Shift Control (Amount of phase variation required, resolution, and required phase vs frequency characteristics)
Response Time of Gain and Phase Controls
Input and Output Impedances (VSWR)
Group Delay Variation
Variation of Phase with Gain Changes
Variation of Gain with Phase Changes
Means of Control (Method of sending control commands to the elements)
Overall Power Consumption

This is a formidable list characteristics which in most cases cannot be determined without a detailed system design and analysis beyond the scope of this study contract.

The task of identifying requirements for MMICs for scanning beam applications can be simplified somewhat by noting some general considerations regarding the three approaches identified above (ie, active phased array, dual reflector with active phase array feed, and dual reflector with active focal plane array feed). The total number of elements in all three approaches is roughly the same and determined

by the total number of beam widths that must be scanned. But the required characteristics of the elements differ considerably. Beam scanning in either of the phased array approaches is accomplished by varying the phase of the elements, whereas in the focal plane array approach beam scanning is accomplished primarily be varying the amplitude of the elements with phase variation only a fine adjustment. This has many implications. In a transmitter array the focal plane array approach suffers from the disadvantage that since only a few of the sources are effective at a time it may not result in the combination of enough elements to produce the desired radiated power. In addition it is difficult to achieve high efficiency at the same time that the power output of the individual elements is varied over a wide range. On the other hand, the phase array approach places significantly more difficult requirements on the phase characteristics of the variable phase shifters. In particular in wide band applications one must maintain a true time delay characteristic over this wide band which may require the use of the switched line phase shifters with long (multiple wavelength) switched lines. Thus, it is possible for the phased array approach to be superior for a transmitter array, where many power sources must be combined; and a focal plane approach to be more advantageous for a receive array.

It will be noted that the phased array approach for a transmit array, rather than the focal plane approach, is attractive from a reliability point of view since the phased array degrades gracefully with the loss of power sources, whereas a focal plane array may lose coverage.

It should also be noted that if the main motivation for the phased array approach is to obtain a sufficient number of power sources, in some situations a combination of the phased array and switched beam approaches is appropriate. That is, a phased array can be used for scanning one dimension while a switched beam is used for the other dimension.

The use of MMICs as the active elements in space based active arrays has received considerable attention. Of most interest has been transmitter arrays for the downlinks at around 20 GHz, receiver arrays at 30 and 44 GHz, and both receive and transmit arrays for intersatellite links at 60 GHz. In particular, of course, NASA has sponsored a great deal of development for the 30/20 GHz application; such as 20 GHz transmitter MMIC development at Rockwell International Corporation and Texas Instruments, receiver MMIC development at Honeywell Corporate Technology Center and Hughes Aircraft, and antenna development at Comsat, Harris, and General Electric. As a result of these studies the requirements for the MMICs for this type of application are well defined.

For example, the block diagrams of the required MMICs for the 20 GHz transmit arrays and 30 GHz receive arrays are shown in Figures 3-6 and 3-7 along with the electrical performance goals.(20)

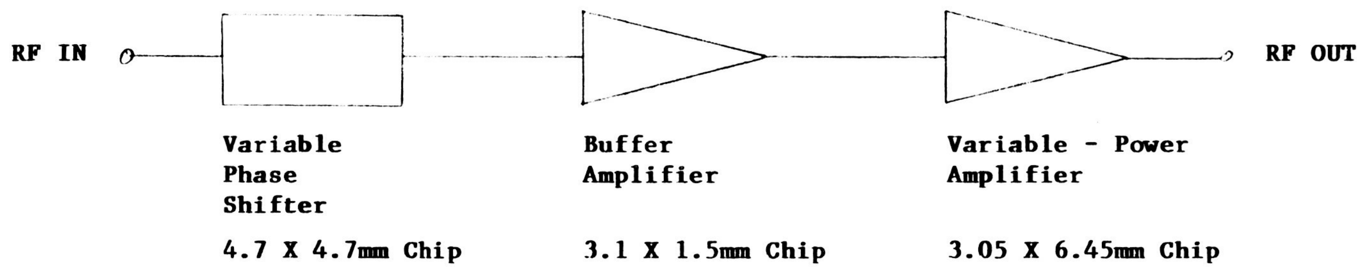
The 30/20 GHz array applications have already been studied in detail on the above mentioned programs. On this program, two additional, but somewhat different, array applications will be discussed in the following two sections.

3.2.2 X-BAND BEAM FORMING NETWORK

As an example of the use of MMICs in an active array, a present X-Band system was considered and a comparison was made of the present implementation using a passive beam forming network with a possible implementation using active MMIC elements. The present X-band receive beam forming network uses ferrite phase shifters and variable power dividers between each of the 61 antenna elements and the receiver as shown in Figure 3-8. Since the loss of the beam forming network adds directly to the receiver noise figure, the loss must be minimized by using a waveguide combining network, with the result that the network weighs 125 lbs.

The use of MMICs in an active beam forming network promises significant advantages over a beam forming network using ferrite phase shifters and variable power dividers. By introducing gain at each receiving element, the loss of the network no longer adds directly to the receiver noise figure. As a result the combining network can be realized in stripline, for example, at a substantial saving in size and weight over the waveguide network while still providing good receiver sensitivity. There is a penalty in terms of DC power consumption by the active elements, but the savings in size and improved performance is significant. In addition, use of the MMICs offers flexibility and trade-offs in the beam forming network design which can be used to optimize system performance. As an example, Table 3-2 shows an estimated comparison of receiver system performance using the passive beam forming network and one possible MMIC realization illustrated by the block diagram of Figure 3-9. This comparison assumes an MMIC amplifier module with 4 dB noise figure. it also assumes that the passive BFN is followed by a receiver with a 3 dB noise figure and a gain of 40 dB, and a gain of 30 dB. The MMIC realization has only about on-fifth the weight of the passive version, with better sensitivity and switching time. By redistributing the gain between the front end and the back end of the combining network electrical performance can be traded with DC power consumption.

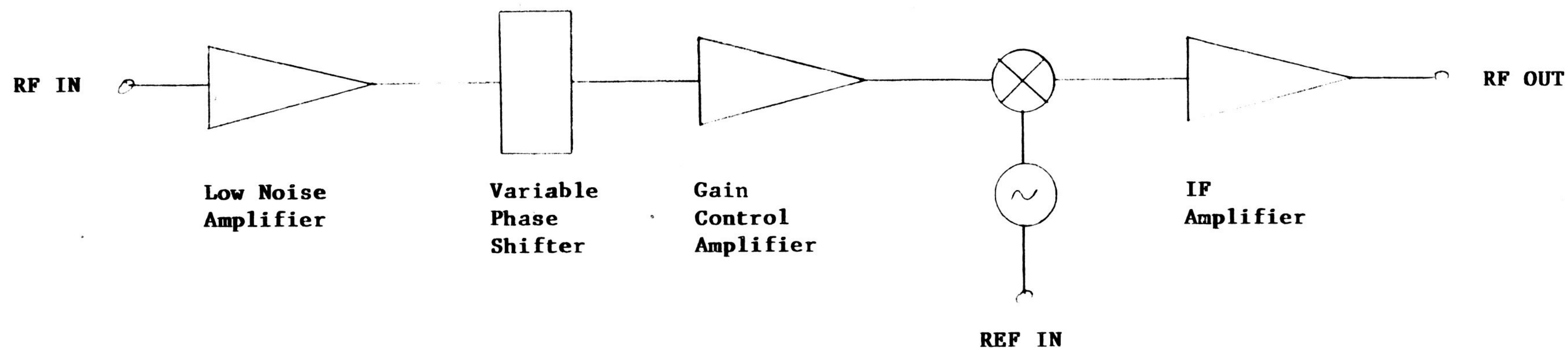
20 GHz TRANSMITTER MMIC MODULE



FREQUENCY:	17.7 - 20.2 GHz
PHASE SHIFTER:	5-Bit (11.25, 22.5, 45, 90, 180 Degrees) Zero dB Gain
BUFFER AMPLIFIER:	16 dB Gain 200 mW Power Output 15 % Efficiency
VARIABLE - POWER AMPLIFIER:	500, 125, 50, 12.5 or Zero dBm Power Putput 20 dB Gain (max) 15 - 6 % Efficiency (Depending on Gain)

FIGURE 3-6 20 GHz Transmitter Module

30 GHz RECEIVER MMIC MODULE



FREQUENCY:	27.5 - 30 GHz
LOW NOISE AMPLIFIER:	30 dB Gain 4.8 dB Noise Figure
GAIN CONTROL AMPLIFIER:	12, 9, 6, 2, - 1 dB and OFF
PHASE SHIFTER:	Five-bit, 6 dB Loss (Max)
OVERALL NOISE FIGURE:	5 dB

FIGURE 3-7 30 GHz Receiver Module

X-BAND PASSIVE BEAM FORMING NETWORK (FERRITE)

FOR ANTI JAM ANTENNA

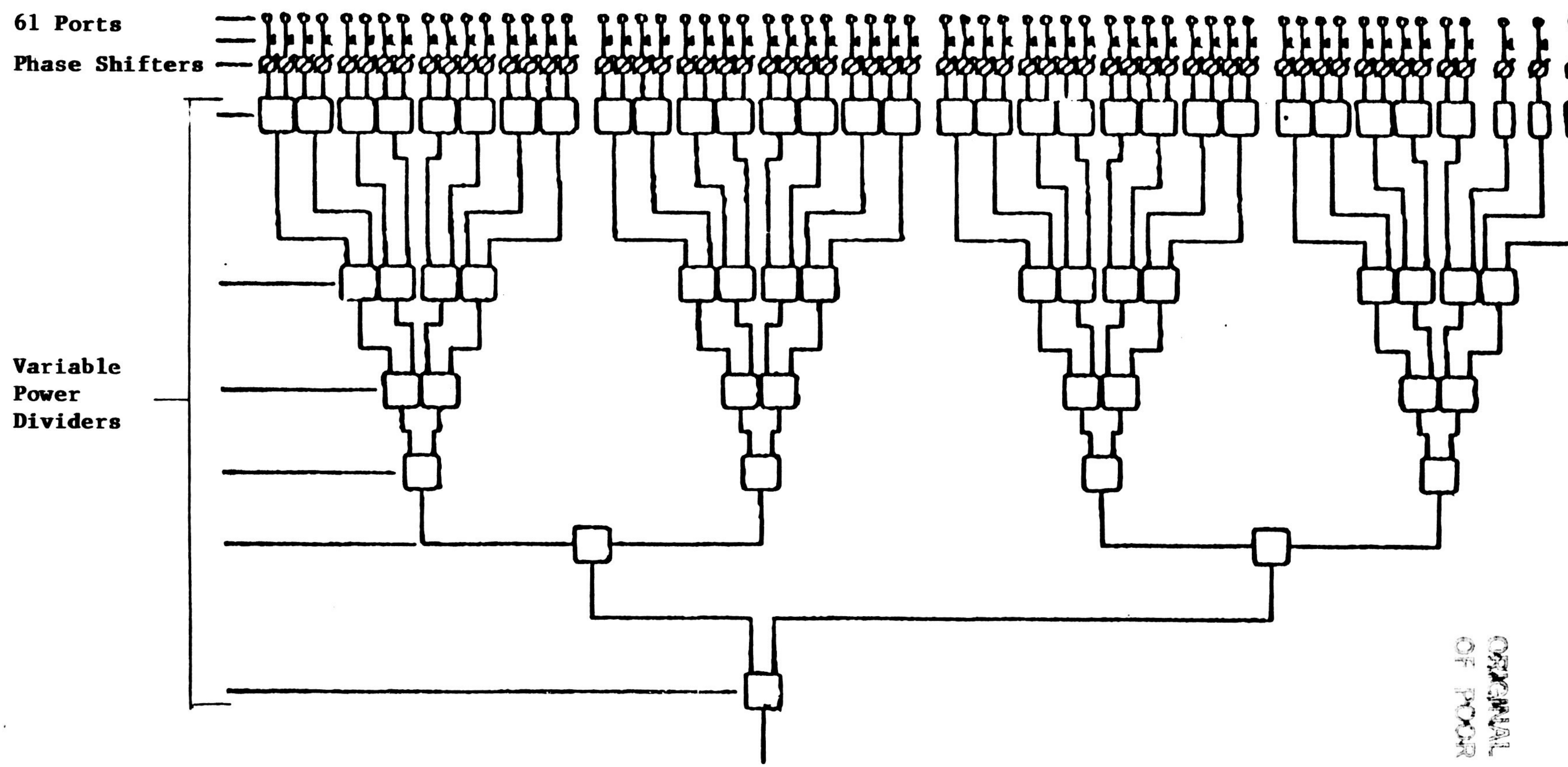


FIGURE 3-8 Block Diagram Of An X-Band Beam Forming Network

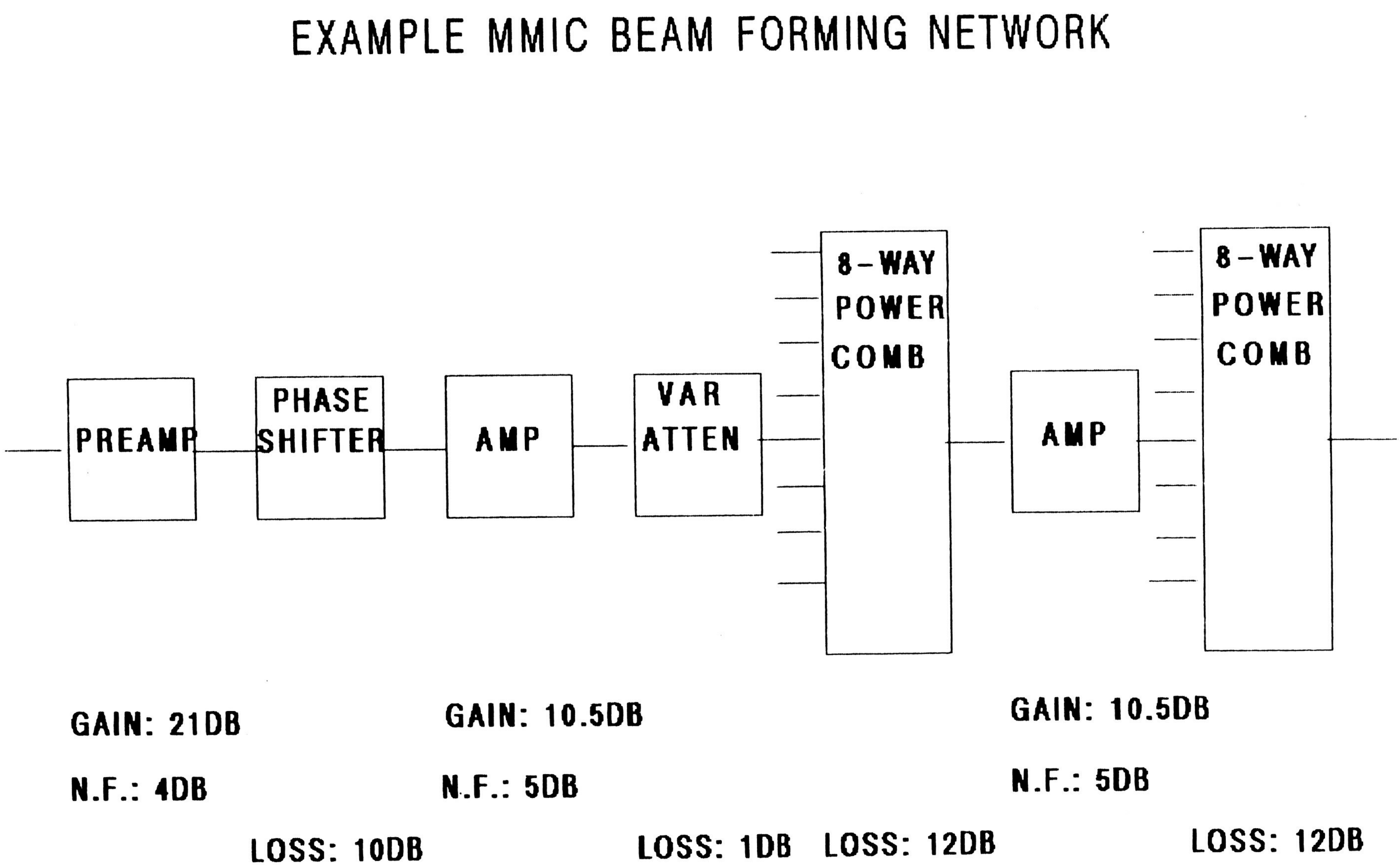


FIGURE 3-9 Possible MMIC Realization of X-Band Beam Forming Network

TABLE 3-2

COMPARISON OF MMIC AND PASSIVE

X-BAND RECEIVER BEAM FORMING NETWORKS

PARAMETER	PASSIVE BFN	MMIC BFN
GAIN OF BFN	-3.1 dB	7.0 dB
SYSTEM GAIN	36.9 dB	37 dB
SYSTEM NOISE FIGURE	6.1 dB	5.5 dB
POWER CONSUMPTION	0 Watts*	17.5 Watts (@ 6 Volts)
SWITCHING TIME	4 microsec.	25 nanosec.
WEIGHT	125 lbs.	24 lbs.

*Power is consumed when passive array is reconfigured, so power consumption depends on reconfiguration rate. MMIC array requires very little power for reconfiguration.

The performance shown in Table 3-2 for the MMIC Beam Forming Network is based on the assumption of the following performance for the MMIC chips:

- FREQUENCY:............. 7.9-8.4 GHZ
- PREAMPLIFIER:.......... 21 dB Gain and 4 dB Noise Figure
- PHASE SHIFTER:......... 5 bits and 10 dB Insertion Loss
- VARIABLE GAIN AMPLIFIER: 10 dB Gain Max and 5 dB Noise Figure
- AMPLIFIER:.............. 10 dB Gain and 5 dB Noise Figure

It can be seen that the MMIC approach offers a dramatic weight reduction which should result in either a cost savings or overall system improvement by trading the weight saving to, for instance, increase transmitter power. The performance of the MMIC version is better, and the power penalty may not be significant depending on the reconfiguration rate. Finally it would be expected that the recurring cost of the MMIC approach would be significantly less.

3.2.3 ON BOARD BEAM FORMING

The present TDRSS system transmits signals from each of thirty antenna elements to the ground where the signals are processed. This approach is wasteful of the frequency spectrum and is subject to degradation due to differential phase shifts in the space to ground links. In addition, the problems with this approach will become more severe when it is desired to increase the numbers of beams and users. Processing the signals on board the spacecraft has the potential to overcome these problems, but adds considerable complexity to the satellite and is

practical only if the microwave circuitry required to implement it is very small, light weight, and cost effective.

System studies for NASA-Goddard are underway at the present, and many system architectures are being considered and tradeoffs are being evaluated The future capability of MMIC technology will play an important role in determining what is achievable and practical. As an example, one possible system implementation has been studied in order to try to quantify the possible benefits of an MMIC realization.

The example which was studied is shown in Figure 3-10. Here 127 antenna elements are used to service six users. In this example, 127 receiver modules and 762 phase shifters would be required. In this example, the phase shifters operate at the receive frequency of 2.29 GHz, but other architectures are being considered in the system studies in which the phase shifters operate at an IF frequency and mixers are included in the receiver modules.

An estimate has been made of the size and weight of the phase shifter and receiver modules of Figure 3-10 using both projected MMIC technology and the main competing technology, hybrid MIC. It was assumed that the phase shifter is a five-bit unit which needs to operate only over a narrow band. Because of the low frequency, a switched-transmission line type of MMIC phase shifter in which variable gain amplifiers using, for example, dual-gate FETs, control the amplitudes of two orthogonal signals, thereby controlling the phase of the signal which results from combining these two orthogonal signals. Using either of these phase shifter approaches or a combination of them, it is estimated conservatively that the five-bit phase shifter could be achieved on a 0.25" by 0.25" GaAs chip.

A similar type of phase shifter could be built, alternatively, in hybrid MIC circuitry using chip semiconductor devices and passive circuitry on alumina substrates. The size of such a hybrid approach is estimated to be 2" by 0.4".

Either the MMIC or the hybrid phase shifter would be packaged in a hermetically sealed package, such as one type of state-of-the-art package which uses a copper-tungsten base (for good thermal conductivity and thermal expansion) and a kovar wall and lid. Such a package can be constructed with ceramic feed throughs for easy integration with microstrip circuitry. A package of this type provides the hematic seal and good RF performance at this frequency, while minimizing the size. The resulting packages for the MMIC and hybrid MIC approaches are sketched in Figure 3-11.

The weights of these two units were calculated to be 37.3 grams for the hybrid MIC phase shifter and 4.9 grams for the MMIC version. For the example system which uses 762 phase shifters per spacecraft this represents about 28.4 kg for the hybrid approach, and 3.7 kg for the MMIC approach.

This represents a very substantial benefit from the use of the MMIC approach.

If a common estimate of $50,000 per kg is used to translate this weight saving in to satellite cost benefit, the conclusion is that a $1.2M advantage per flight would be achieved from the weight saving of the MMIC approach.

This $1.2M estimated benefit is from weight savings alone. At the relatively large quantities involved, the recurring cost of the MMIC phase shifters should be substantially less in itself than the cost of the hybrid version.

Although no detailed studies have been made of the layout of the system, it is clear that size will be a significant constraint. The 127 band pass filters would consume substantial space to achieve low loss, thereby increasing the need to minimize the size of the other RF components. It is possible that the size advantage alone of the MMIC approach would be an enabling benefit.

The MMIC approach would be expected to have significantly better reliability than the hybrid approach. Although the number of active elements and their temperature would be equivalent, the large number of wire bonds in the hybrid approach will significantly reduce the predicted MTBF.

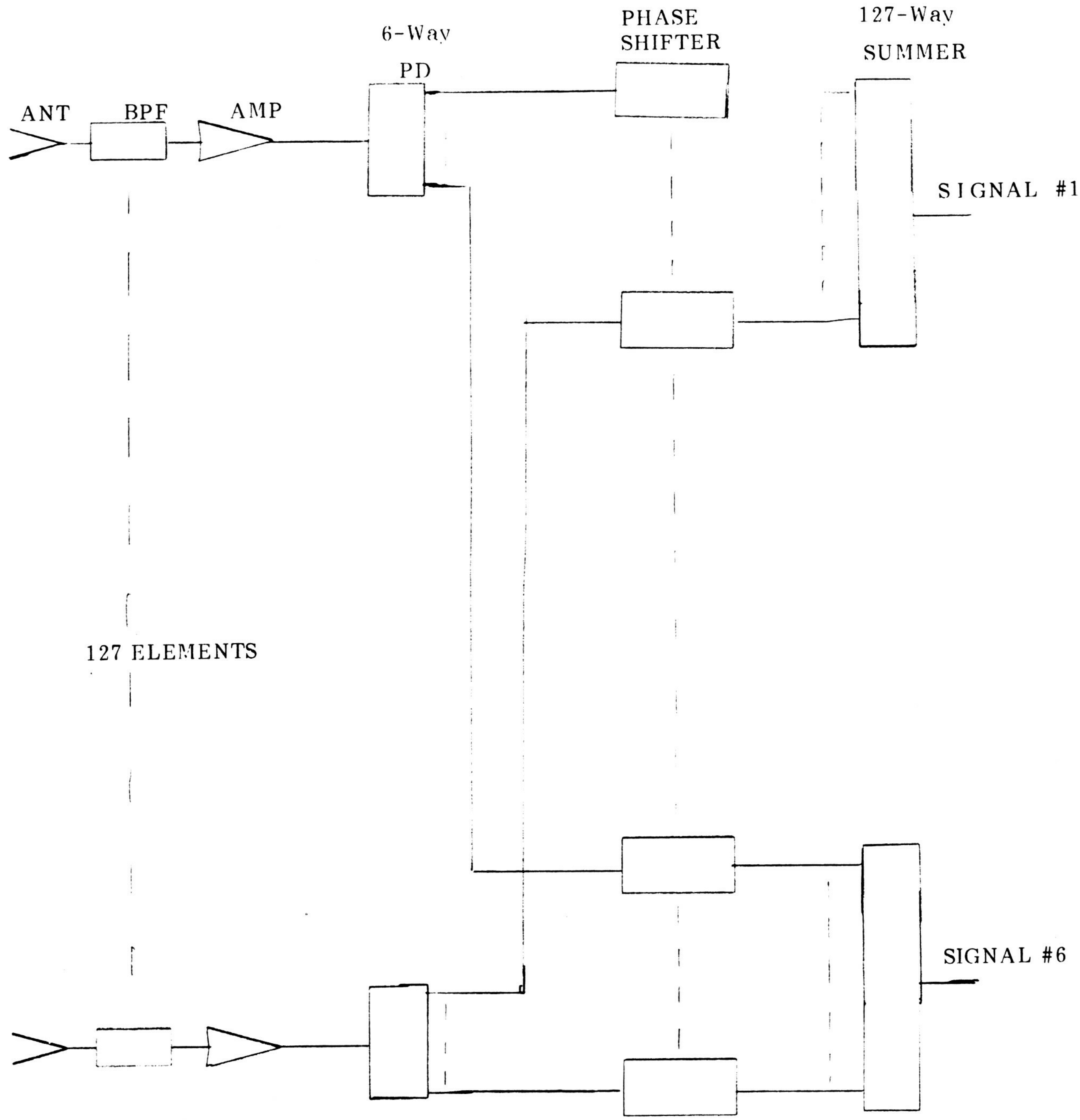


FIGURE 3-10 Possible Implementation Of On-Board Beam Forming System

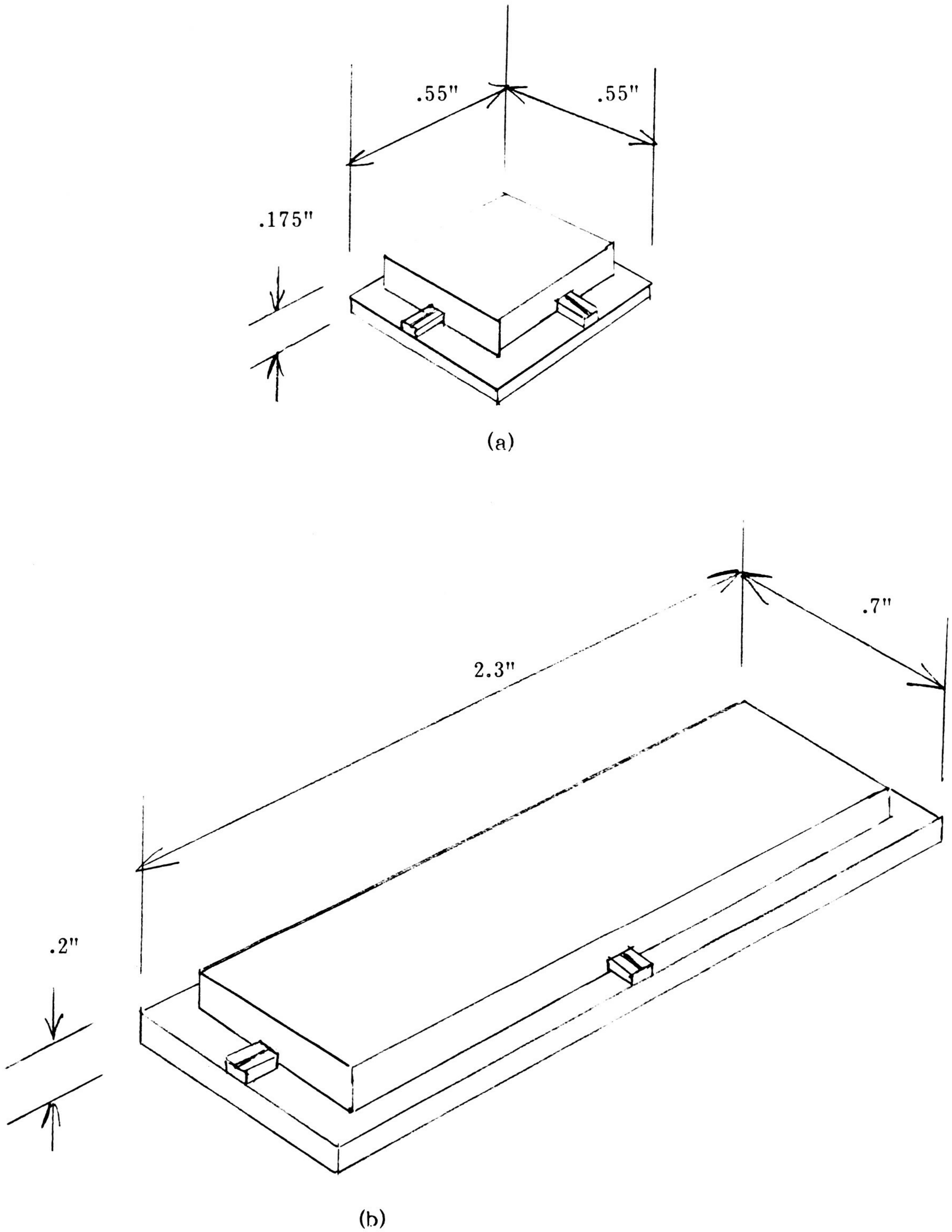


FIGURE 3-11 Projected Size of (a) MMIC Phase Shifter Module and (b) Hybrid MIC Phase Shifter Module

Finally, as in other array type applications, an advantage of the MMIC approach is that the electrical characteristics of the modules should track better over temperature than the hybrid modules. This will in turn simplify the required control and calibration procedures.

Thus far, only the advantages of realizing the phase shifters in MMIC form have been considered explicitly. Many of the same advantages would accrue from using monolithic technology for the preamplifiers, but in this case the advantages are not so great because of their smaller numbers and the expectation that in the case of the preamplifiers some performance degradation in noise figure would have to be traded against the size and weight advantage. The size and weight saving per preamplifier would be approximately the same as for the phase shifter, about 32 grams per unit. Thus for 127 amplifiers the saving would be 4 kg. This, alone with the size advantage, which may be very important, and the reliability and temperature tracking advantages, may well make the MMIC approach significantly superior for the preamplifier as well as the phase shifter.

The electrical performance which would be required of the phase shifter for this on board beamforming system is estimated to be:

CENTER FREQUENCY........................ 2.29 GHZ
BANDWIDTH............................... 100 MHz max
PHASE INCREMENTS........................ 11.25 degrees (5 bits)
LOSS.................................... 10 dB approx
VSWR.................................... 1.25:1 max

At this rather low frequency a switched transmission line phase shifter of the type used at higher frequencies would be too large. However, if FET single- pole double-throw switches are used to switch between high and low pass filter sections, instead of transmission lines, the phase shifter could be realized on the small chip assumed in the preceding analysis. Lumped element spiral inductors and MIM capacitors would be used to form the low and high pass filter sections. The approach is similar to that used by Maloney, Selin, and Jones in L-Band.(21)

3.3 APPLICATIONS OF MMICS IN INTERPLANETARY COMMUNICATIONS

As discussed in Section 2.5.1 a major factor in determining the technology required for future deep space and interplanetary missions is the planned move from X-Band to Ka-Band for the communications for such missions. The move is motivated by the approximately 8 dB improvement in performance resulting from the higher gain produced by the same size antenna at the shorter wavelength. This 8 dB advantage can be used to decrease power consumption, reduce antenna size, or increase communication capacity depending on the priorities of the mission.

For instance, in some types of probes power is extremely expensive. DC power is obtained from radio isotope thermonuclear generators (RTGs) at a cost of $200,000 per Watt. Simplistically, use of Ka-Band potentially could reduce DC power consumption of the transmitter by 8 dB, assuming the same efficiency of DC to RF conversion can be achieved at the higher frequency. On the other hand in some missions, physical constraints may make it necessary to use the smaller antennas permitted by the higher frequency.(14)

JPL has outlined a sequence of developments to exploit the advantages of the higher frequency, and MMIC technology plays a major role in making this possible. This chain of development activities is described in the following paragraphs.(17)

3.3.1 KA/X-BAND TRANSMISSION EXPERIMENT ON THE MARS OBSERVER (16)

Ka-band space link development is to begin with a Ka-Band Link Experiment (KABLE) on the Mars Observer spacecraft.(16) The block diagram of the KABLE equipment is shown in Figure 3-12. KABLE is not expected to use MMICs, but will provide transmission data and establish the dish antenna approach to used for Cassini. X-band power will be provided by a TWT and the fourth harmonic will be used as the Ka-band source. The Ka-band signal is fed through the center of the primary reflector and reflected back onto the primary reflecting surface by a dichroic (frequency selective) subreflector. The X-band signal will be fed through, and unseen by, the dichroic subreflector. Transmission parameters on X and Ka-bands will be compared.

3.3.2 COMET RENDEZVOUS ASTEROID FLYBY (CRAF)(17)

A Ka-band exciter and power amplification module will be developed and demonstrated on CRAF. The power amplifier module is required to produce 250mW with 25 percent power added efficiency and must be small and low cost. The power amplifier may be a MMIC chip or MMIC chip followed by a discrete FET output stage. In addition to its use on CRAF, the module will be an important development step towards the Cassini feed array which is discussed in the next section. A reflector/subreflector parabolic dish antenna discussed for the MOS KABLE will be used for CRAF. Figure 3-13 illustrates the CRAF communication subsystem. This is different from the MOS subsystem by the addition of the Ka-band amplifier module and feed. Figure 3-14 illustrates the amplifier module and feed configuration in more detail. Circular polarization is required which is obtained by delivering two wavefronts in 90 degree quadrature to the antenna. The challenge to MMIC technology to be applicable to CRAF is to provide space qualifiable chips within the CRAF timetable and to meet the efficiency requirements.

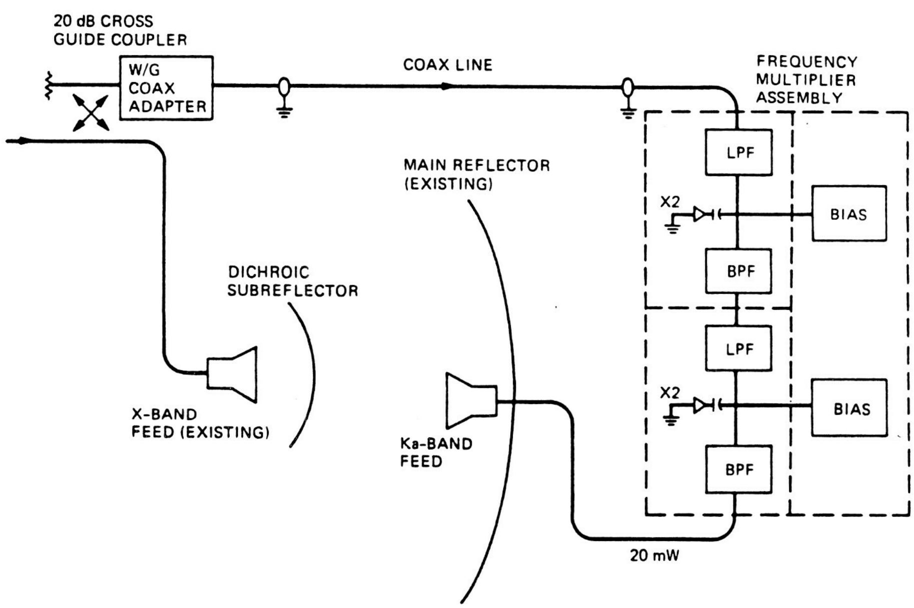


FIGURE 3-12 Mars Observer Ka-Band Link Experiment (KABLE) Block Diagram (JPL Figure)

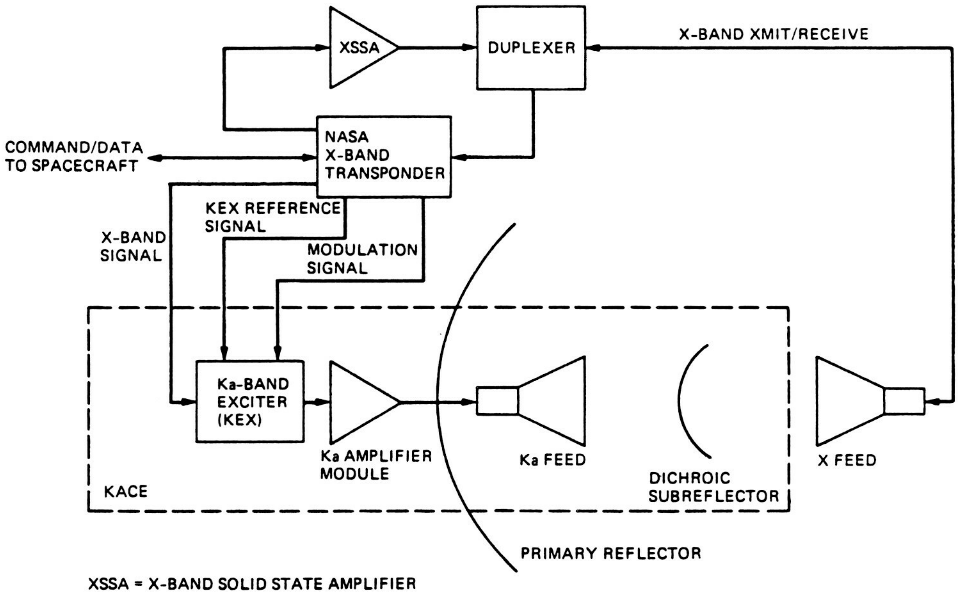


FIGURE 3-13 Interface for the CRAF Ka-band Communications Experiment (KACE)

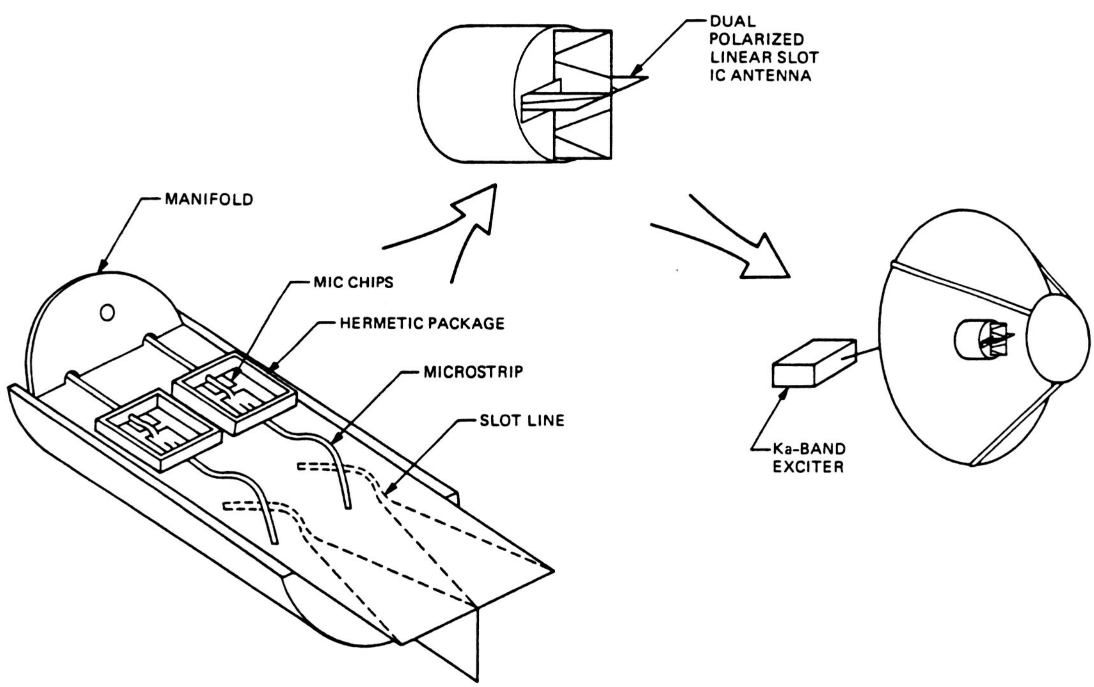


FIGURE 3-14 Configuration of the Ka-band Beacon Experiment System.(JPL Figures)

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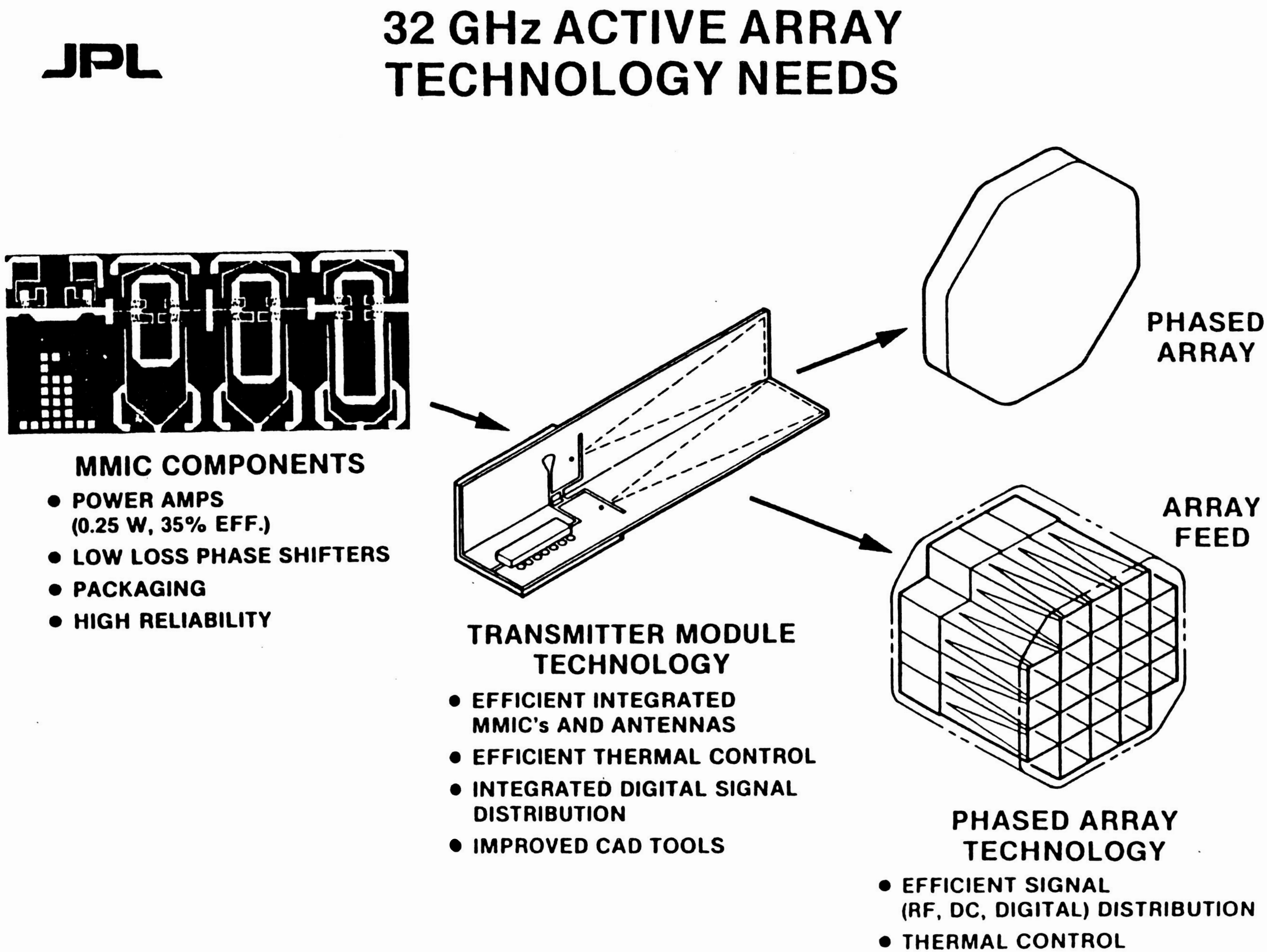


FIGURE 3-15 32 GHz Active Array Technology Needs (JPL Figure)

3.3.3 32 GHZ ACTIVE ARRAY TECHNOLOGY FOR CASSINI AND MSR

The basic MMIC technology proposed by JPL for use on Cassini and MSR type missions is illustrated in Figure 3-15. Here the motivation for the use of MMIC technology becomes clear as power amplifiers similar to those of CRAF will be combined with phase shifters and control electronics to provide an active array with electronic beam steering. The transmit module contains a phase shifter and power amplifier, 90 degree quadrature radiating elements, and the module enclosure. For this application MMICs would offer the benefits they typically provide to active arrays: small size to fit the constraints of the array, repeatability to provide good tracking, and possible cost benefits because of the quantities involved.

JPL has studied the benefits of the 32 GHz approach in comparison to a current X-Band downlink.(14) The 8 dB advantage resulting from the use of 32 GHz could be used to increase the data rate by a factor of five using the X-Band antenna size and baseline power consumption. On the other hand it could be used to reduce the antenna size. In the case of the Cassini probe it was concluded that the most advantageous use of the 8 dB was to decrease the power consumption. The JPL study showed that a 25 Watt RTG could be eliminated in this way at a $5M saving, overcoming an estimated $3.4M increased recurring cost of the array. JPL estimated the non-recurring development cost to be $7M.(14)

A strawman downlink system for Cassini uses twenty-one elements, spaced 1.8 wavelengths (1.7 cm), each radiating 100 mW.(17) Twenty-one of the modules are illustrated in the Figure 3-15 for use in feeding a parabolic dish antenna for Cassini missions. Figure 3-16 shows the dish antenna configuration which is similar to the CRAF antenna. A power added efficiency of at least 30 % was assumed for the power amplifier. Monolithic technology has clear advantages for use in the phase shifter and low power amplifier stages to minimize size and weight and to provide good unit-to-unit tracking. The efficiency of the output stage is critical, so a discrete device in a hybrid MIC configuration may be the preferable approach for the output stage to give optimum performance.

In the case of the Mars Sample Return Mission (MSR), landed mass and size are extremely important drivers. Under the current mission scenario the rover will only communicate with earth when it is not moving; hence the communications hardware can use the power allotted for the locomotion function, so DC power is not a spacecraft driver. The 32 GHz allows for the use of a smaller, lighter antenna than with X-Band. JPL studied two options. One uses a parabolic reflector; the other, a flat plate array. The array provides the better size and mass performance of the two.(14)

Figure 3-15 shows the transmitter module feeding a phased array constructed with patch antenna radiating elements. The phased array antenna is a candidate for MSR and would contain hundreds of elements instead of the twenty-one for the Cassini application. The MSR array

would probably require both amplitude and phase control. Each MSR module would be required to provide between 10 mW and 100 mW. Figure 3-17 depicts the 32 GHz active array technology as envisioned to be inserted into Cassini and MSR (labeled MRSR).

The most challenging technical requirement in this sequence of 32 GHz developments to support these interplanetary missions is the 32 GHz power amplifier. The power output required (approximately 0.25 W) is right around the present state-of-the-art, but the required 30-35 % power added efficiency is significantly beyond current technology.

In addition to the power amplifiers the arrays will require variable phase shifters and variable gain amplifiers at 32 GHz. These should be similar to MMICs being developed for 30 GHz communication satellite uplink arrays except for the slightly higher frequency.

3.4 APPLICATIONS OF MMICS IN SYNTHETIC APERTURE RADARS

As discussed briefly in Section 2.5.3 development of space based synthetic aperture radars is being done at JPL. The Earth Orbiting Satellite (EOS) series will map the surface of the earth as part of the Mission to Planet Earth.

MMICs may play a key role future Synthetic Aperture Radars (SARs). Although SARs have been used in space in the past, future requirements will call for a substantial weight reduction.

SAR missions and systems are:

SEASAT - 1978
SIRA - 1981
SIRB - 1984
Megallan 5TH Shuttle Flight
NASA Scattermetic (NSCAT) - 1993
EOS1 - 1994
EOS2 - 1995
Space Station (Altimeters)
Titan (Saturn moon) Mapper - 2000

The highest frequency demonstrated is 5 GHz with further progression planned as follows:

ROS - 10 GHz, 25 GHz
NSCAT - 14 GHz
Titan Mapper - 35 GHz

The goal for antenna peak output power is 250W to 500W at 10 GHz and 100W to 300W at 24 Ghz. At 24 GHz about 1W per transmit module would be required depending upon how many antenna elements are used.

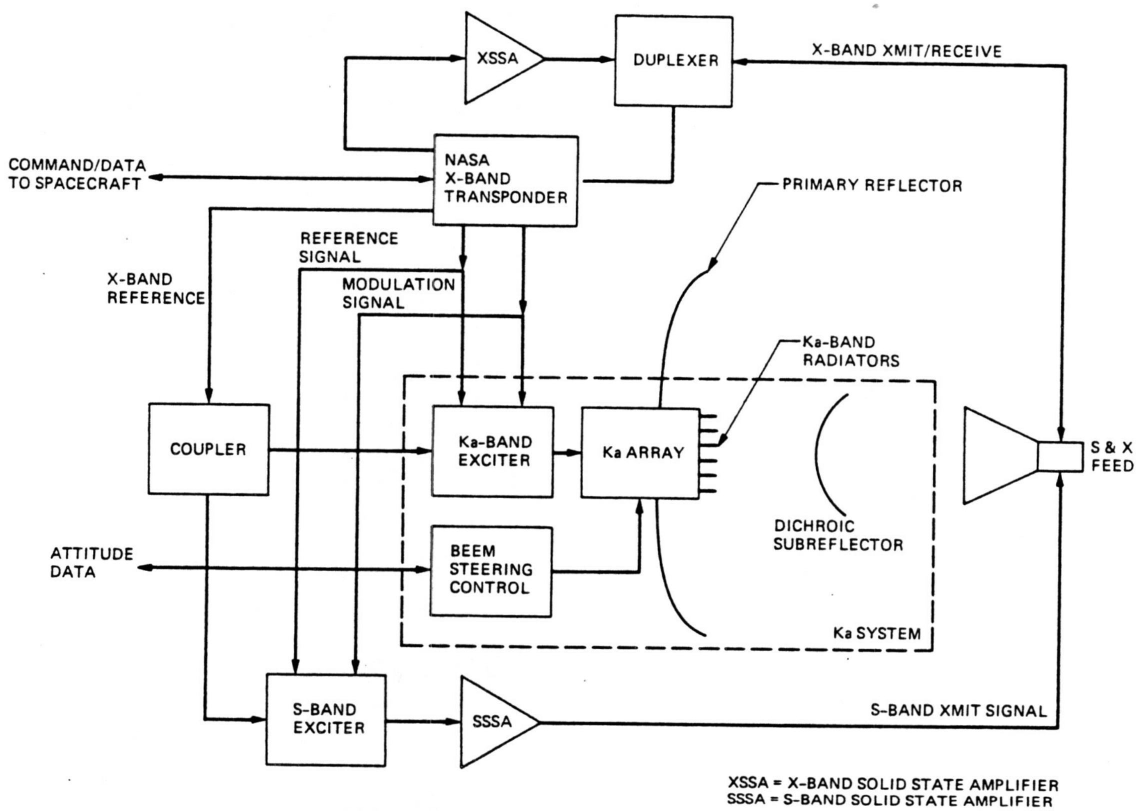


FIGURE 3-16 Cassini Ka-, X-, and S-band Communications System (JPL Figure)

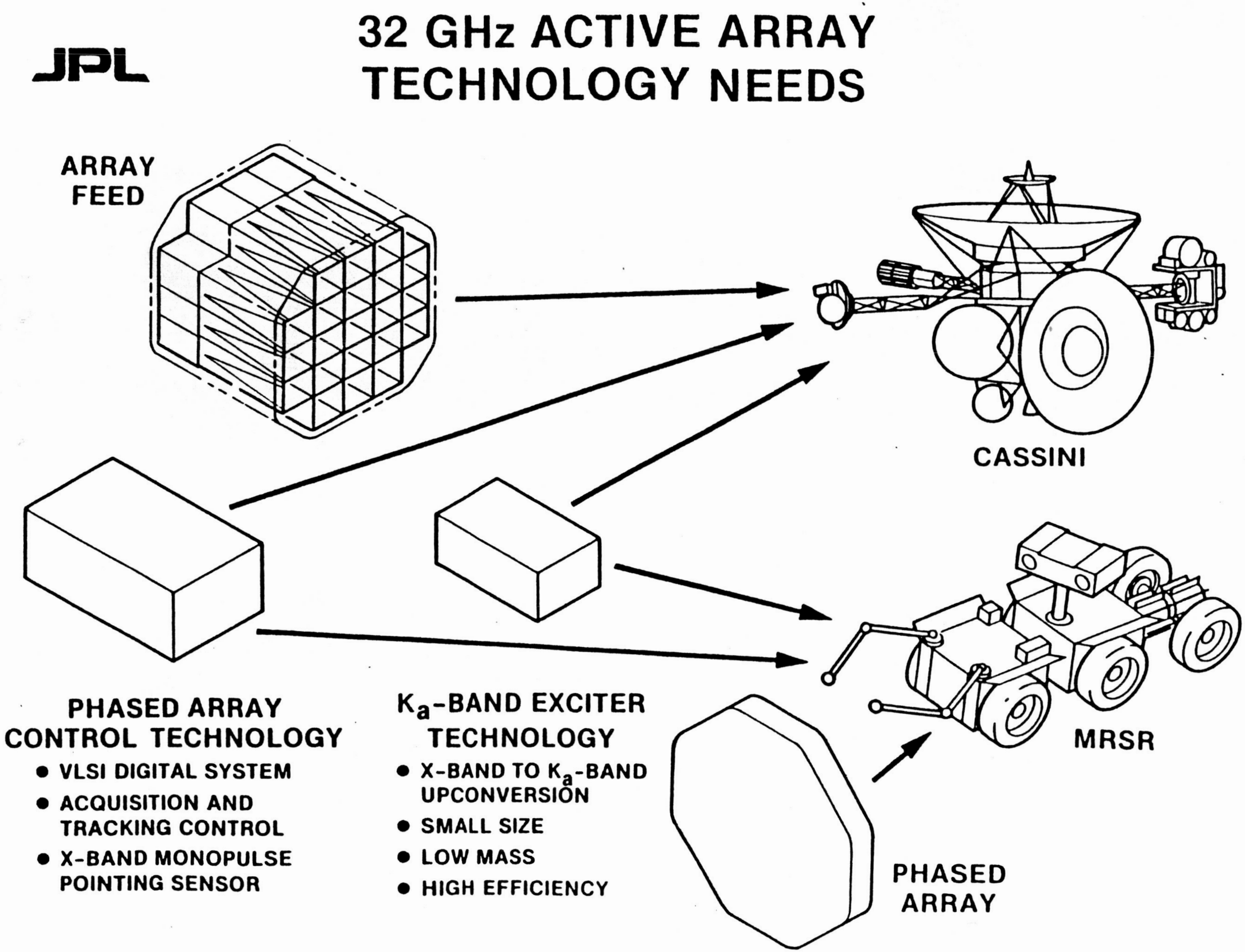


FIGURE 3-17 32 GHz Active Array Technology Needs (JPL Figure)

The primary advantage of MMIC to JPLs radar programs is in weight reduction, and there is an urgent need for this. For EOS a 30% weight reduction in the radar subsystem is required. The present weight is 2500 kg.

Figure 3-18 illustrates the antenna configuration for the distributed element active array synthetic aperture radar. The size is established by the aperture required to meet the SAR performance goals. The frequencies required within the next three years are well within the capability of the current MMIC technology. The feed array module electronics are depicted in Figure 3-19. The circulators in the module would probably be replaced by FET switches for the purposes of size and weight minimization. The module could consist of several MMIC chips and discrete devices integrated in an MIC hybrid configuration. For example, a phase shifter MMIC, FET switch MMIC, driver amplifier MMIC, gain stage MMIC and discrete FETs for power output and low noise input stages could be used.

The mechanical configuration for the SAR feed and antenna array is illustrated in Figure 3-20. The frame size of the array will not change by using MMIC since it is established by the requirements of the array, but the weight will be reduced considerably. Reduction in the weight of the modules mean that the weight of the framework structure will also be reduced, resulting in an even greater weight reduction.

The C-Band radar represents the best SAR application of MMICs. In particular, the five-bit phase shifter should be well within the present capability of custom MMIC circuits. The low noise amplifier with a noise figure of less than 2 dB, while more of a technical challenge than the phase shifter, should also be within the capability of present technology. MMICs can also be used for the first stages of the power amplifier. Thus, except for the output stages of the power amplifier and the circulators, it appears to be very feasible to realize the C-Band module in monolithic form. Its implementation in space qualified MMIC would contribute greatly to the necessary weight reduction of the system and demonstrate the applicability of monolithic technology to space based radars.

It appears that MMICs can be the key to obtaining the required weight reduction in the SAR. The challenge is to bridge the gap between what seems technically feasible and what has been demonstrated to the extent that a commitment can be made to use them in an important space mission.

3.5 APPLICATIONS ON THE SPACE STATION

Section 2.5.5 discussed some of the requirements for communications within the Space Station Control Zone. The initial baseline system is based on the use omni antennas on both the space station and the user vehicles for close in communications, switching to a tracking

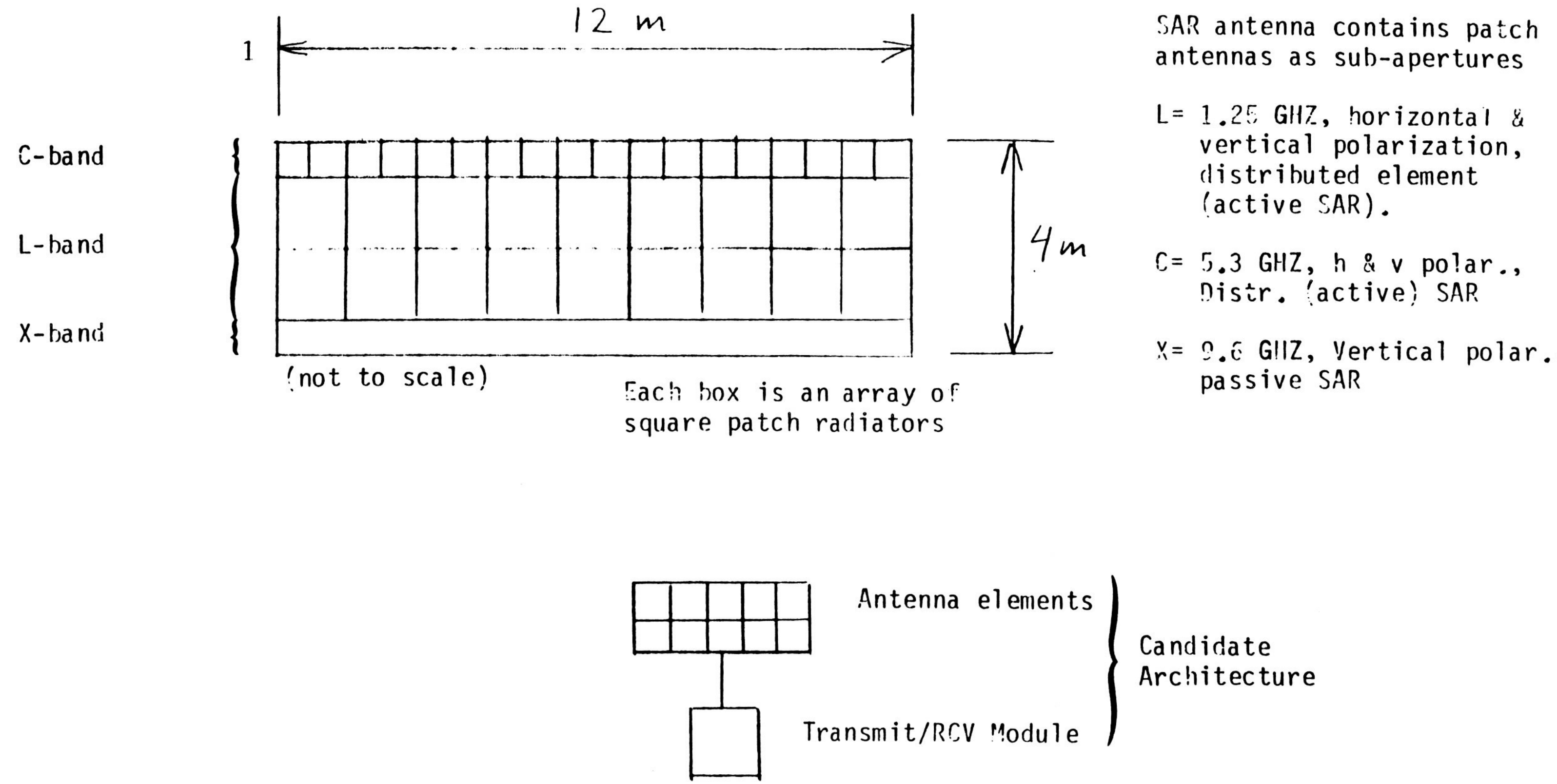
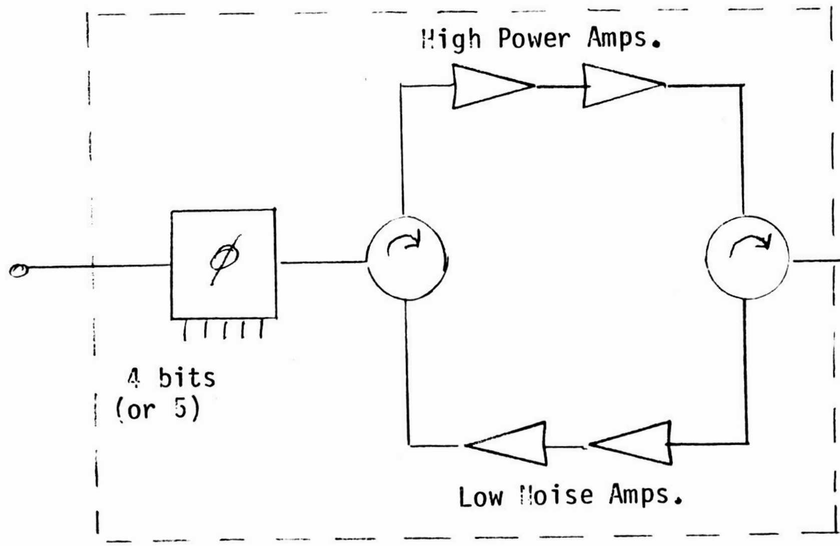


FIGURE 3-18 Distributed Element Synthetic Aperture Radar (SAR) Antenna Configuration



- 12W peak power at C band
- 40W peak power at L band
- < 1.5 dB noise Figure at L band
- < 2.0 dB noise Figure at C band
  pulse repetition Freq.=1200 to
  2000 pulses/sec.
- Bandwidth 10 mhz to 50 mhz
- 250 modules for L band
  500 modules for C band
  - at C-band with 6 percent duty cycle
    720 mw average power required
- power required is traded against
  number of patch antennas per module.
- would like transmit/rcv switch rather than
  circulators.

FIGURE 3-19 Candidate Module Architecture For Active/Distributed SAR

directional antenna on the space station for more distant communications within the control zone. The use of omni antennas on the space station strains the capability of the users at the other end of the link where power may be at a premium. The available DC power at the Extravehicular Activity (EVA) terminal together with the efficiency of the DC/RF conversion sets the maximum distance at which the space station omni can be used, beyond which the tracking directional antenna must be used. On the other hand size, weight, and reliability considerations argue against the use of the many gimbaled parabolas which would be required to accommodate several users.

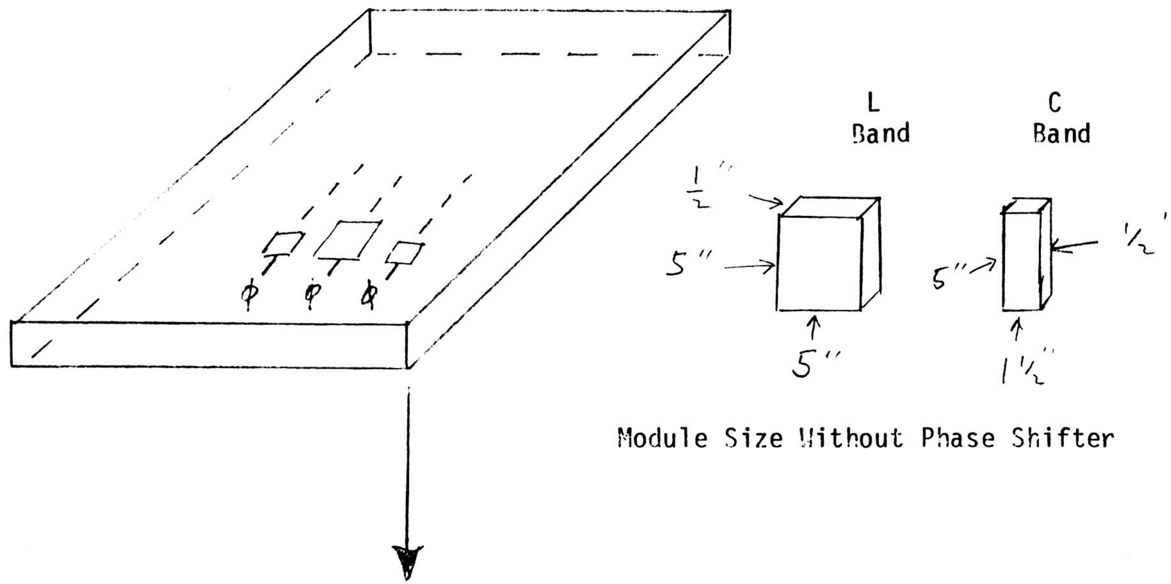
A highly attractive solution, to handle the long term needs of the space station, is the use of an electronically steered, multibeam antenna. This approach is being studied by Johnson Space Center and, under contract to them, by Harris.(22) Johnson built a prototype system in-house using hybrid MICs. Using their approach, a complete system with four channels and a 32 element array covering a hemisphere would require 128 elements.

The approach being studied by Harris would use a four-sided pyramid with 368 elements in each pyramid (92 receive elements, 192 transmit elements forward; 12 receive and 72 elements for the side).(22) With two pyramids per station a total of 736 elements would be required. Since these are the numbers of antenna elements, the number of microwave circuit elements would be the product of these numbers times the number of beams. This number of circuits in K-Band would require the use of MMIC technology to be cost effective.

The Harris study presumably will result in a definition of the requirements for MMICs for this application. The Final Report on that contract is not yet available. The following are goals for the power amplifier circuits:

FREQUENCY: 21-23 GHz	
VARIABLE POWER AMPLIFIER:	2 Watts maximum power, 15 dB gain, 30 % efficiency (monolithic)
MEDIUM POWER AMPLIFIER:	2 Watts power, 15 dB gain, 30 % efficiency (monolithic)
HIGH POWER AMPLIFIER:	6 Watts power, 15 dB gain, 25 % efficiency (hybrid)

Possible MMIC applications also exist for the far range communication for the Space Station. This is for communication to satellites in the 37 km to 2000 km range. It requires an antenna with 37 dB of gain, but with limited scanning(possibly +/- 5 degrees and +/- 1 degree in azimuth). Approximately 100-200 elements may be required.



Module Size Without Phase Shifter

Radiation direction is downward from bottom surface

Antenna subsystem size is fixed because aperture size is fixed. Present weight is 2500 kg but require 30% reduction for EOS.

FIGURE 3-20 Distributed Antenna and Active Feed Array Mechanical Description

3.6 APPLICATIONS IN ON BOARD SIGNAL PROCESSING

As indicated in Section 2.4 satellites have the potential for revolutionizing communications by linking the world wide communications network directly to the individual. Initially this will take the form of an extension of VSAT technology to provide two-way voice communications bypassing the terrestrial segment. It will also take the form initially of mobile communi- cations to trucks and cars. It could eventually lead to truly personal communications linking all individuals who wish to be linked to the communications network through small portable terminals.

To accomplish this requires making the satellite perform the tasks now served by the master, hub earth stations of the VSAT systems. This implies a great deal of on board signal processing such as demodulation and modulation, decoding and encoding, and RF and baseband switching. Much of this capability does not explicitly fall in to the category of Monolithic Microwave Integrated Circuit, but since in many cases it does require high speed GaAs digital ICs beyond the present state-of-the-art, some of these requirements will be touched on here briefly.

A number of studies (2,11) have identified a bulk demodulator as a key technology for satellites to serve a very large number of small users with VSATs. The optimum satellite, from the point of view of minimizing earth terminal costs, is one that uses continuous low data rate carriers on the up-link and high burst rate TDMA on the downlink. To make such a system practical requires a bulk demodulator, also known as a multicarrier de- modulator, capable of accepting as its input a large number of equally spaced carriers, demodulating the carriers, and determining the bits carried as information on them.

For example, Figure 3-21 shows a possible architecture from Future Communications Satellite System Architecture Concepts (11). Each of four uplink beams has a receiver consisting of a low noise amplifier and downconverter covering the 500 MHz communications band. The IF signal is filtered into 25 MHz segments before being input to a set of bulk demodulators. The input to each bulk demodulator can contain as many as 400 channels separated in frequency (FDM). The demodulator outputs a serial bit stream with the individual channel bits separated in time (TDM). The bulk demodulator hypothesized in that study was capable of demodulating 400 signals of 72 kbit/s at one time.

Figure 3-22 shows one bulk demodulator concept(11). The demodulator accepts the IF signals from the downconverter, and performs the analog selection and downconversion to a second IF of limited bandwidth on the order of 10 MHz. The exact bandwidth depends on the number of channels demodulated at one time and the communication rate on each channel. The second IF is arranged to lie from 0 Hz to about 10 MHz so that the signal may be converted to digital form for further processing. The sample rate for the A/D converter must be at least twice the bandwidth.

(11) describes the bulk demodulator concept in detail and makes size and weight estimates for the postulated satellite system using four uplink beams. Estimates were made for both 1990 technology using VLSI chips using a technology such as CMOS, and projected 1995 technology using GaAs VLSI. The results are shown in Table 3-3.

TABLE 3-3

ESTIMATED BULK DEMODULATOR MASS AND POWER CONSUMPTION (11)

	1990 TECHNOLOGY (CMOS VLSI)	1995 TECHNOLOGY (GaAs VLSI)
MASS(per satellite)	127.4 kg	63.7 kg
POWER CONSUMPTION (per satellite)	1542 Watts	450 Watts

Clearly the implementation of the GaAs technology for the demodulator would have a significant impact on the economics and feasibility of such a system.

It has been recognized for some time that an IF switch matrix will be an important element of advanced communication satellites. Early development of 4 GHz switch matrices was done by Ford Aerospace under NASA-Lewis sponsorship in the early 1980s. This early work used hybrid MIC construction and dualgate FETs as the switching elements in a crossbar switch arrangement. MMIC technology makes possible a large size reduction of such switches.

Such an MMIC IF switch matrix is being developed for NASA by Microwave Monolithics, Inc. FETs are used for switching and for buffer amplifiers. Whereas a hybrid MIC switch matrix (100 X 100) will weigh 227 kg (500 lb) and consume approximately 0.2 cubic meters (12,000 cubic inches) of volume, a monolithic GaAs version will weigh only 7.7 kg (17 lb) in 0.003 cubic meters (200 cubic inches).(20)

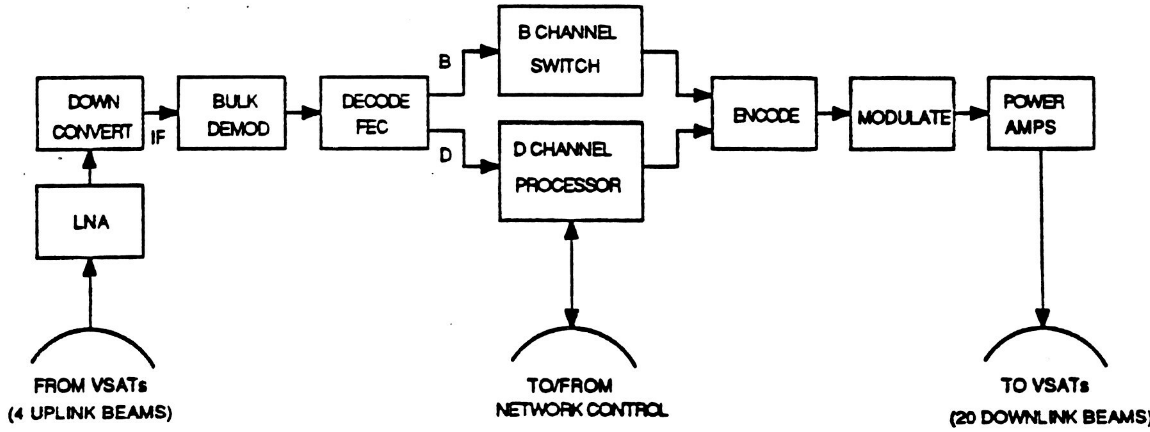


FIGURE 3-21 Proposed Architecture For System To Service Large Numbers Of VSATs

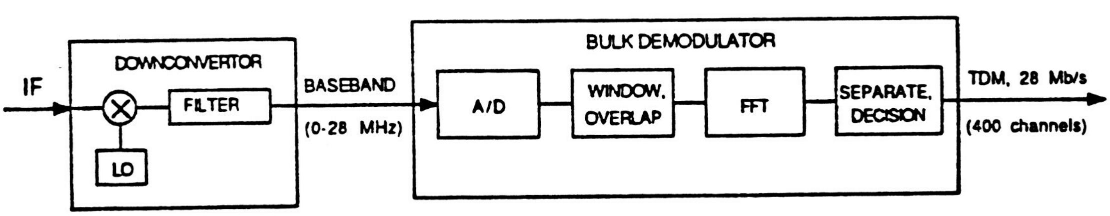


FIGURE 3-22 Proposed Bulk Demodulator Concept

4.0 TECHNOLOGY ASSESSMENT

In this section the present state of MMIC and competing technologies is assessed, as it relates to the applications identified in the preceding sections. In addition projections are made for future technology developments. The following technologies are evaluated because of their relevance to the identified applications:

1. MMIC design and fabrication techniques
2. Hybrid MIC techniques
3. Millimeter-wavelength power devices and MMICs
4. Millimeter-wavelength low noise devices and MMICs
5. Photonic technology for active arrays

4.1 MMIC DESIGN AND FABRICATION TECHNIQUES

During the past ten years dramatic strides have been made in the technology of Gallium Arsenide Monolithic Microwave Integrated Circuits (GaAs MMICs). These developments have demonstrated the potential of this technology for opening up new systems opportunities by making it possible to accomplish microwave circuit functions in a physical size or at a cost which would be unattainable using conventional microwave circuit technology. This technology has obvious potential benefit for space-based equipment because of its ability to radically reduce the size and weight of microwave circuitry and its capability for realizing functions which would be impractical with conventional techniques.

Figure 1-4 showed a photograph of a two-stage 20 GHz MMIC amplifier, an MMIC developed by Ford Aerospace and processed by Ford Microelectronics, Inc. It uses most of the techniques which are typical of current MMICs: FETs (with one-half micron gates in this case), plated through vias to bring the ground connection from the ground plane on the bottom of the chip to the appropriate points on the top, MIM capacitors formed using silicon nitride dielectric deposited by plasma enhanced chemical vapor deposition, air bridges, and thin film resistors. The circuit along with many other circuits of the same and different types were fabricated on a single 3 inch diameter Gallium Arsenide wafer, as shown in Figure 1-4. Typical process steps are outlined in Table 4-1, and described briefly as follows:

TABLE 4-1
TYPICAL PROCESS STEPS FOR MMIC FABRICATION

1. Alignment target etch
2. Isolation
3. N+ implant
4. N+ implant
5. Ohmic contact
6. Gate
7. Thin film metal resistor
8. First overlay metal
9. Dielectric
10. Second overlay metal
11. Air bridge via
12. Air bridge metal
13. Scribe street
14. Through wafer via

1. The alignment target etch is used for patterning and etching the alignment keys for future mask alignment.
2. Inter-device isolation is provided by the semi-insulating substrate, by mesa etch isolation, or by deep H+ ion implantation.
3. The N+ implant defines the contact regions and N+ resistors.
4. The N implant defines the N regions for the active devices.
5. The ohmic contacts for the active devices are formed.
6. The gate of the FET is formed by a lift-off process.
7. NiCr resistors are formed. 8. Metal 1 overlay defines the first level interconnects, transmission lines, bottom electrodes for MIM capacitors, and contact pads for vias.
9. The silicon nitride capacitor dielectric is deposited.
10. Metal 2 overlay defines the top electrodes for MIM capacitors, intermediate interconnects, and air bridge contact pads.
11. Air bridge via is the first step in forming an air bridge.
12. The air bridge is plated to the desired thickness and the resist removed to leave the bridge free standing.
13. Scribe streets are etched to facilitate dicing.
14. Wafers which require vias are thinned, vias are patterned and etched from the back side, and then the backside and vias are plated.

The cross-section of the resulting structure is shown in Figure 4-1. Processing a 3 inch GaAs wafer such as that of Figure 1-4 produces a very large number of MMIC chips, assuming the typical chip is on the order of 1 or 2 square millimeters in size. For large production situations the entire wafer can be devoted to replicating a single design. On the other hand for experimental, development work or other situations where only small quantities are required of any particular circuit, many different circuits can be placed on the wafer as is the case with the wafer of Figure 1-4.

Clearly since the cost of processing a wafer is large, the cost of the resulting MMIC chip depends strongly on the size of the circuit and the yield of good devices. A 3 inch wafer can yield, in principle, over 4000 one-square millimeter chips. If the cost of processing this wafer is $10,000, and the yield is 10%, the cost of a good chip is $25. These numbers are fairly typical. It can be seen that yield and circuit size have high leverage in determining the cost of the MMIC.

Thus, the circuit of Figure 1-3 is not typical of a production MMIC, since it is rather casual in its use of GaAs area, using distributed chokes and matching circuits. Partly, this is because it is a high frequency (20 GHz) amplifier, so it is reasonably small even though no attempt was made to minimize the size, and partly it is a result of the fact that this is an experimental circuit and it was desired to avoid difficult-to-characterize proximity effects. A more typical production circuit is shown in Figure 4-2. Here the size has been minimized by the use of lumped elements and a very dense layout. Although the production costs of a circuit such as that of Figure 4-2 is reduced by the compactness of the design, and the higher yield which can result from reducing the circuit size, the development cost may be considerably higher than that of a more conventional design because of the many design iterations necessary to accumulate the empirical design information. Iterations are expensive in time as well as money since the cycle of design, mask layout, mask fabrication, wafer processing, and test can easily consume 4-6 months and $50,000 to $100,000.

Thus, there is a trade-off between development cost and production cost which must be considered in a particular application.

MMIC technology based on GaAs MESFETs is now well established for use to 18 GHz. A recent survey identified over fourteen companies offering GaAs fabrication services with capability extending at least to 18 GHz. In addition several companies are offering standard MMIC products. Another survey identified 300 standard MMIC products being offered, not including GaAs digital ICs. Most of these standard products are very broadband amplifiers and control devices, using monolithic technology's unique capability for very broadbandwidths to make devices which the manufacturers hope will be usable in many applications. As a result of the wide bandwidth of most of these standard products, they do not offer the optimum performance for the narrow bandwidths typical of communication applications. (An exception is a low noise 9-10 GHz amplifier offered by TI).

Thus, the technology is well established for frequencies through 18 GHz. MMICs have been built at least on an experimental basis to at least 94 GHz. The major consideration in extending MMIC technology to frequencies greater than 18 GHz is the smaller geometries required for the active devices. Good performance can be achieved through 18 GHz using FETs with 0.5 micron gate geometries. Such devices can be

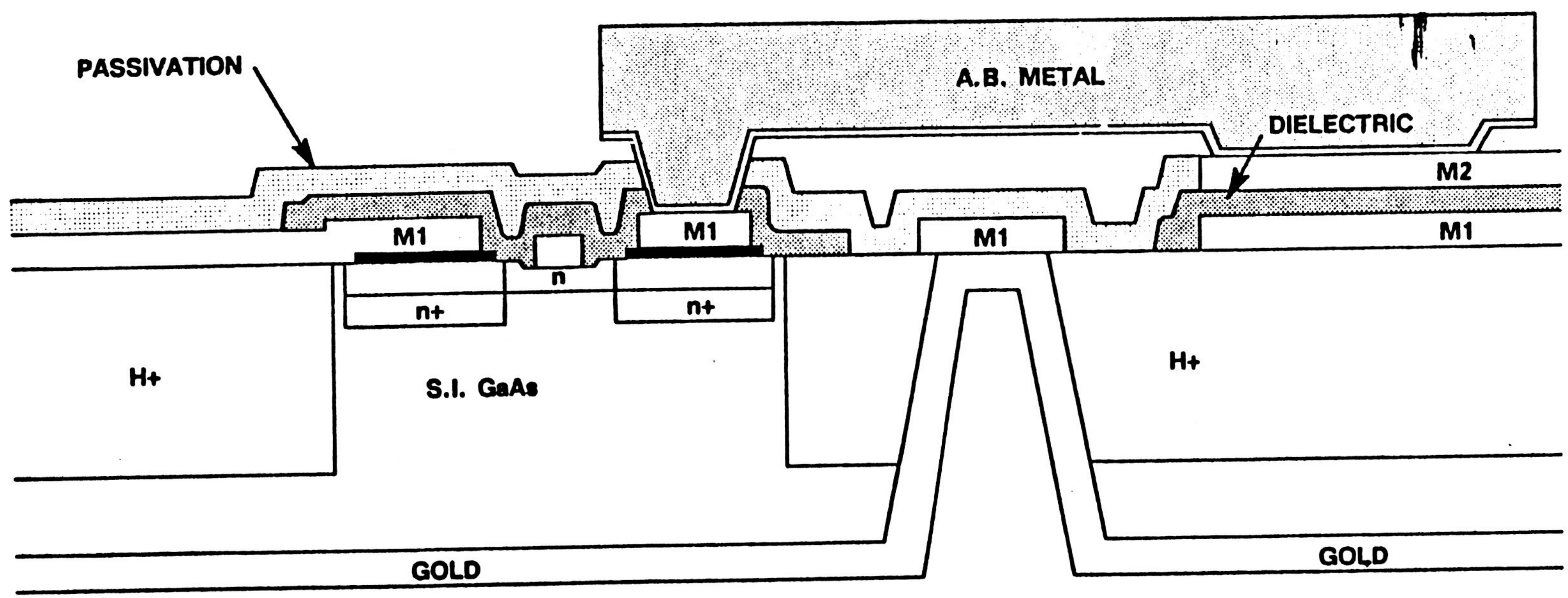


FIGURE 4-1 Cross Section Of MMIC Produced By The Process Of Table 4-1

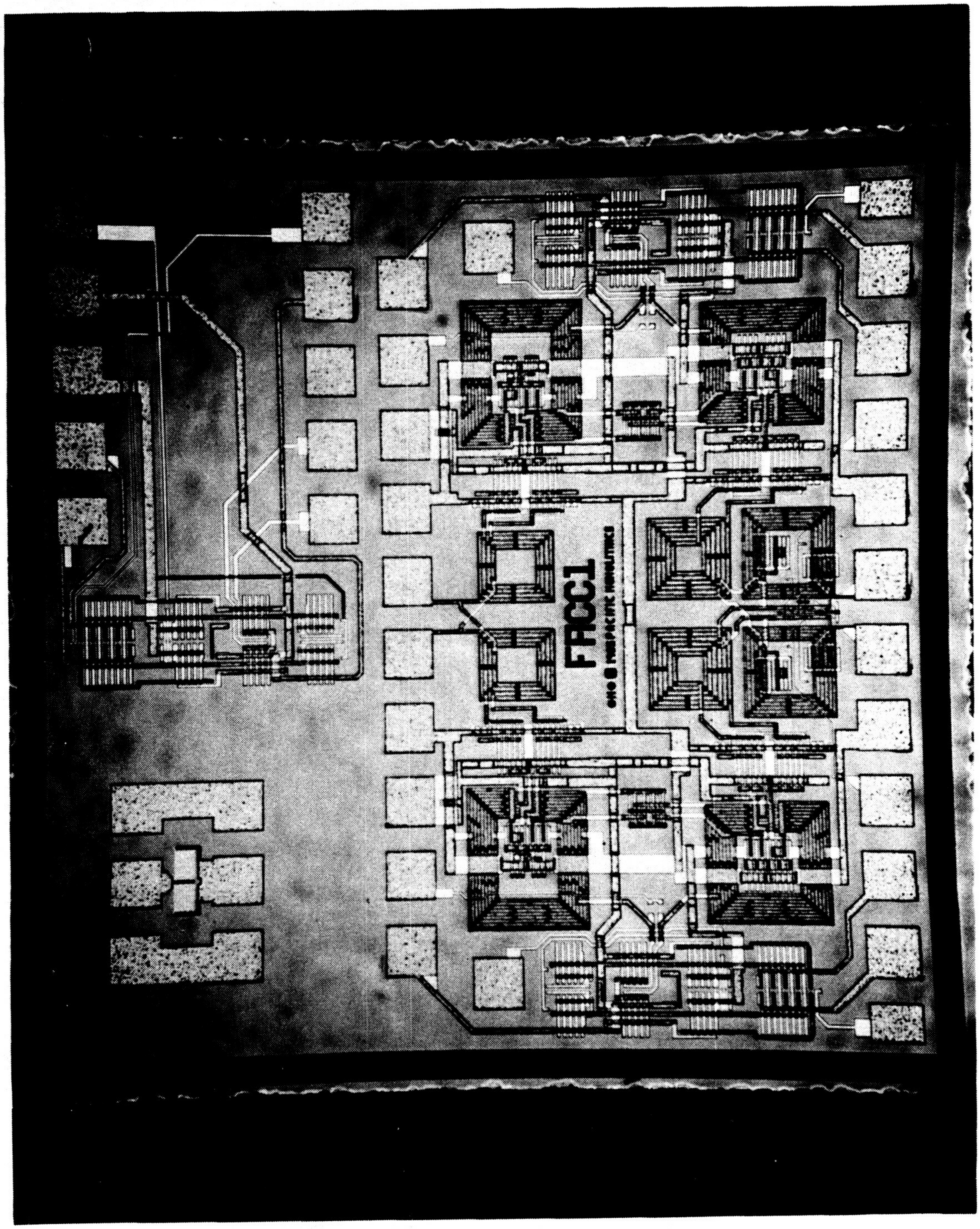


FIGURE 4-2 An MMIC Using A Densely Packed Design
To Minimize Production Cost

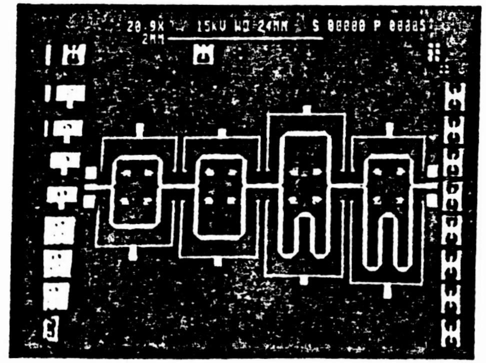
fabricated with good repeatability and yield using optical lithography. For good performance at higher frequencies gate dimensions of 0.25 microns or less, and gate cross sections in the form of a "TEE" or "mushroom" are required. Such geometries require more sophisticated lithography such as E-beam or ion-beam lithography, and even then economical yields are difficult to achieve. In addition, as described in the following sections, the best performance at frequencies above 18 GHz requires more complicated materials such as heterostructures fabricated using advanced techniques such as Molecular Beam Epitaxy (MBE) or Metalo Organic Chemical Vapor Deposition (MOCVD), and the complexity and criticality of these materials further hinders the yield, so that these state-of-the-art millimeter wavelength devices have so far been achieved with small yields in the form of discrete devices rather than as MMICs.

Considerable development of millimeter-wavelength MMICs has been done under the sponsorship of NASA, the Air Force, and private industry. MMICs include low noise and power amplifiers, phase shifters, switches, and variable gain amplifiers. The status of low noise amplifiers and power amplifiers will be discussed in the following sections.

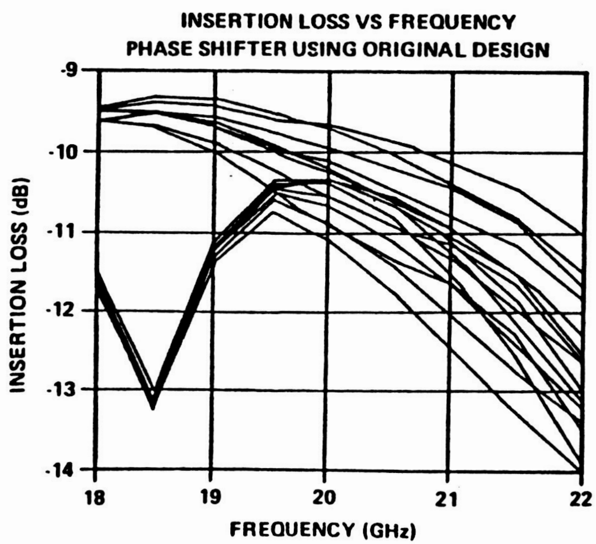
Control circuits such as phase shifters and switches are more easily fabricated for millimeter wavelengths than amplifiers since they can be made satisfactorily with larger gate geometries. Figure 4-3 shows a photograph of an experimental 4-bit, 20 GHz phase shifter developed by Ford Aerospace and fabricated by Ford Microelectronics. FETs with one micron gate length were used as SPDT switches to switch appropriate lengths of transmission line. The figure also shows the measured performance. The phase shift as a function of frequency shows the expected characteristics of a true time delay type of phase shifter. The loss is approximately 2.5 dB per bit. The loss varies by about +/- 0.8 dB as the phase state is varied. Although this loss variation is better than some reported results(23) for some applications better performance would be required. Careful modeling of the switched FET elements and computer optimization of the circuit shows that better loss constancy could be achieved by a more sophisticated design.

Figure 4-4 shows some preliminary results on 44 GHz MMIC phase shifters. In this circuit 0.5 micron FETs are used as the switching elements. Figure 4-5 shows the results of testing the switch elements alone. By measuring the s-parameters of the switching FETS accurately using a 50 GHz Cascade Microtech probe it will be possible to optimize the phase shifter design. These 44 GHz circuits, also, were designed and evaluated at Ford Aerospace and fabricated at Ford Microelectronics.

4 BIT PHASE SHIFTER AT 20 GHz



CHIP SIZE: 2.6mm X 5.5mm



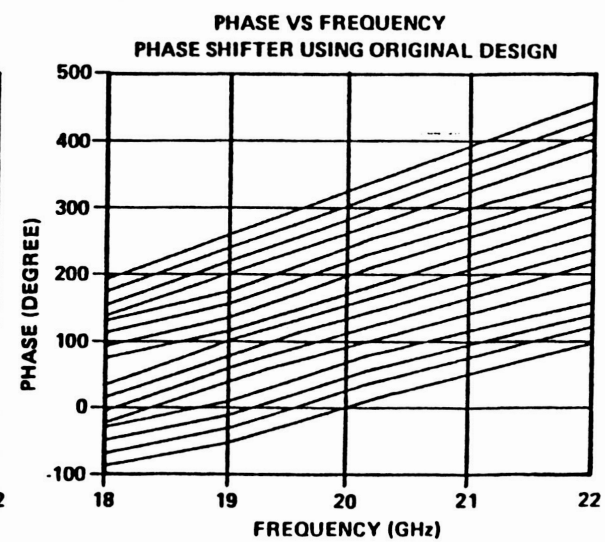


FIGURE 4-3 Photograph Of Experimental 4-Bit, 20 GHz Phase Shifter And Experimental Results

Thus development of millimeter-wavelength switches is well underway and the main objective of future work will be to reduce the loss and loss variation, and to integrate the phase shifters with other RF and control circuitry.

4.2 MILLIMETER-WAVELENGTH POWER DEVICES AND MMICS

4.2.1 THE PRESENT STATE-OF-THE-ART

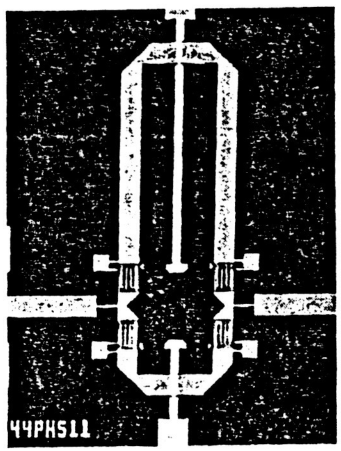
At present, there are three major device approaches for power device applications: Power MESFET, Power HEMT(High Electron Mobility Transistor), and Power HBT (Heterojunction Bipolar Transistor). Although there are other device structures such as PBT, or Permeable Base Transistor, these three are the mainstream.

The cross-section of these power device structures are shown in Figure 4-6. In the field-effect transistors (MESFET and HEMT), current flows horizontally through a narrow conduction channel parallel to the device interfaces, while in the HBT, it flows vertically through the interfaces. As a result, bipolars exhibit higher current gain and less trapping, both of which are important for precision analog circuits. FET threshold characteristics depend on the doping and thickness of the channel and gate process. For HBT's, threshold uniformity is controlled by the energy gap discontinuity of the emitter-base junction, which is grown into the material. As a result, HBTs exhibit superior device matching characteristics. While FETs exhibit nearly square law transfer characteristics, HBTs exhibit exponential transfer characteristics that are better suited for realizing nonlinear functions.

The state-of-the-art results for power MESFETs, HEMTs, and HBTs, are summarized in Table 4-2 and are discussed briefly below.

The MESFET technology is the most established and mature among the three. TI reported a GaAs Power MESFET with 41% power-added efficiency at 35 GHz.(24) In this work, the devices use a 0.25 um gate on MBE-grown active material and an n^+ ledge channel structure. COMSAT reported Ka and V band power amplifier MMICs using MESFETs fabricated on VPE materials. The Ka band power amplifier achieved a small-signal gain of 4.3 dB and output power of 481 mW with power-added efficiency of 11.3%.(25) These MMICs include DC-blocking capacitors and bias networks. A cascaded four-stage amplifier has a power gain of 18.9 dB and output power of 437mW at 28 GHz. the V-band single stage amplifier has 4 dB gain from 50 to 56 GHz with output power of 95 mW and a power-added efficiency of 11% at 55 GHz.(26) A four stage amplifier achieved 16.2 dB gain and 85 mW output power. By using a Be co-implantation technique, Toshiba developed high-power and high-gain GaAs MMICs at 29.5 GHz with an output power of 1 W with 4.2 dB gain and 11% power-added efficiency for a 4.8 mm power combined MESFET.(27) This result achieved by combining two 2.4mm MESFETs with 0.5 W output power, 5.3 dB gain, and 16% power-added efficiency.

44 GHz – 180° PHASE SHIFTER MEASURED RESULTS



44 GHz DATA
3.7 dB INSERTION LOSS @ REFERENCE
3.4 dB INSERTION LOSS @ 180°
192° ACTUAL PHASE SHIFT @ 44 GHz

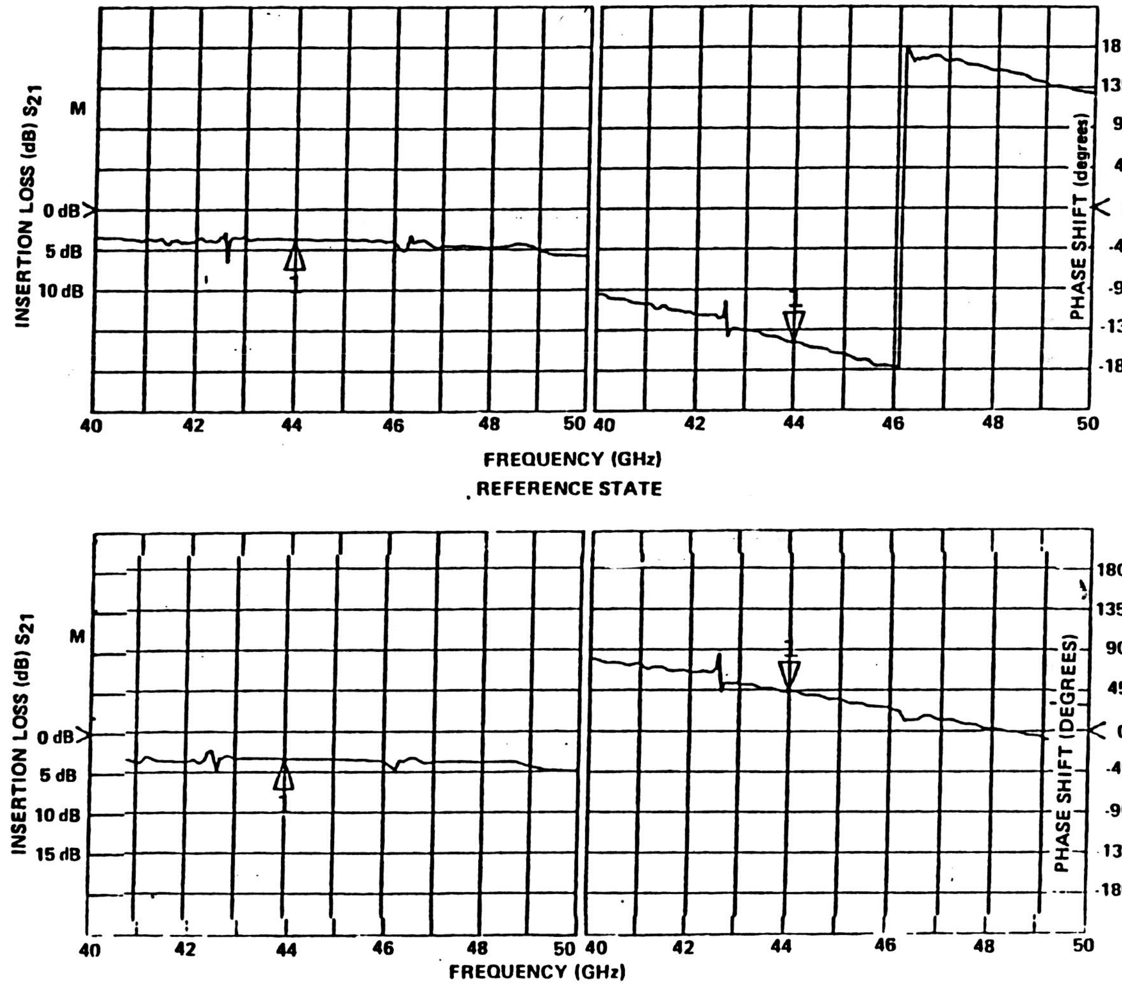


FIGURE 4-4 Preliminary Results On 44 GHz MMIC Phase Shifters

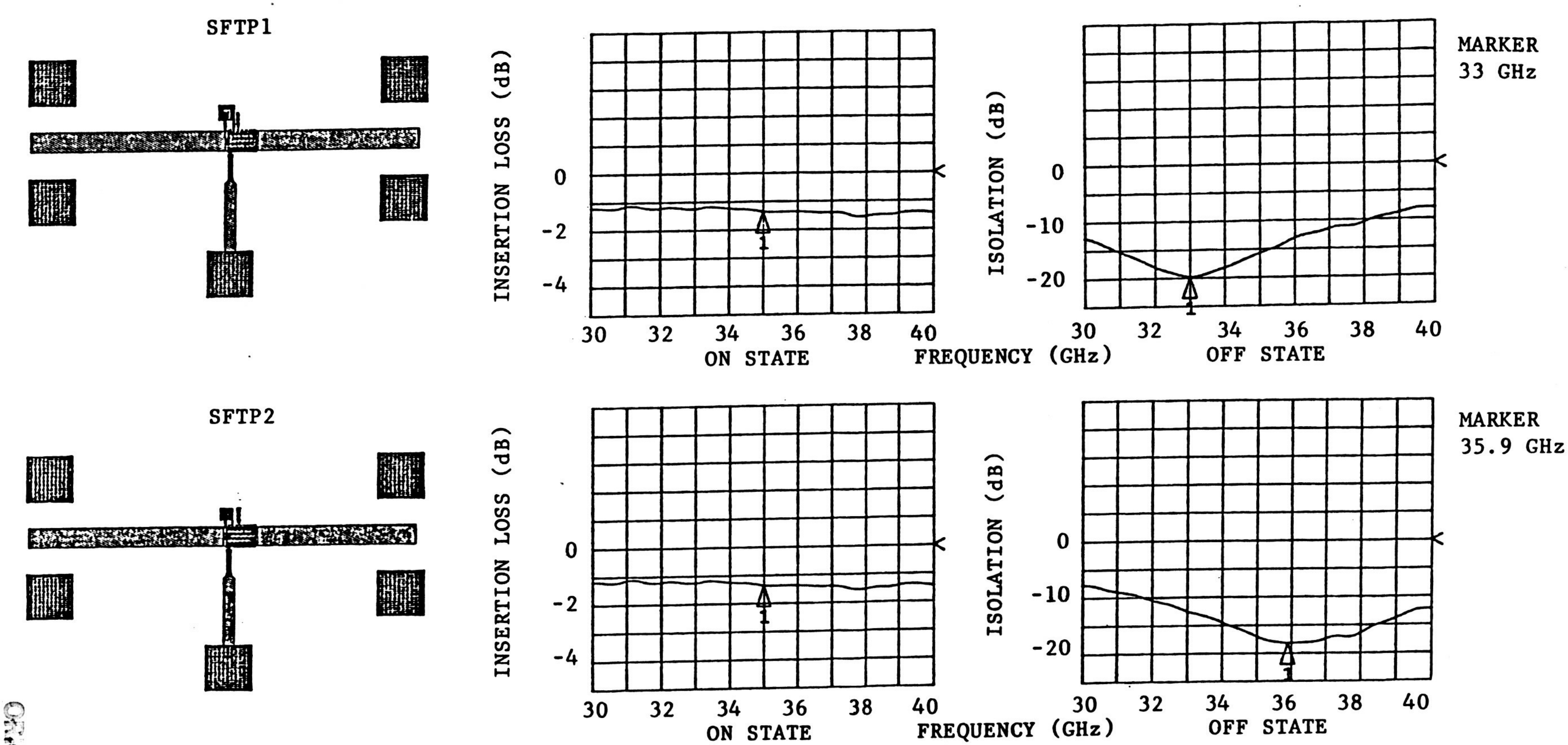


FIGURE 4-5 Experimental Performance of Switch Elements For Phase Shifters

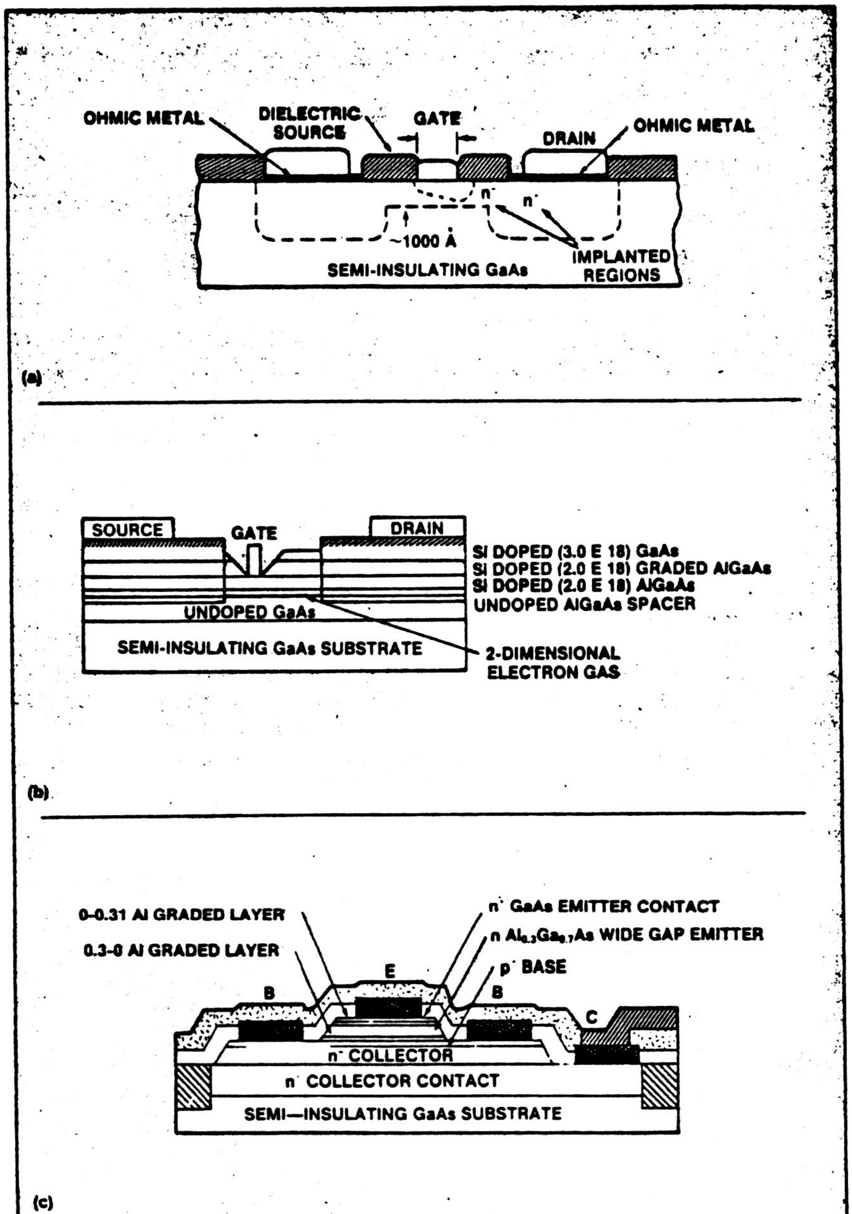


FIGURE 4-6 Cross Sections Illustrating Different Approaches for Power Devices

In the area of power HEMT development, considerable work has been reported in the literature. GE reported excellent power performance for single heterojunction pseudomorphic HEMTs with 0.25 um gate lengths: a power-added efficiency of 28% at 60 GHz and an output power of 9 mW at 94 GHz.(28) By doping on both sides of the InGaAs quantum well, a double heterojunction HEMT with high channel current can be obtained. For these HEMTs, 0.9 W/mm at 35 GHz and 0.7 W/mm at 60 GHz were achieved. These HEMTs have also yielded 44% maximum efficiency at 35 GHz and an output power of 100 mW at 60 GHz. Cornell reported a high-current pseudomorphic AlGaAs/InGaAs double quantum-ell MODFET with f_t of 52 GHz and f_{max} of 110 GHz.(29) This device has a maximum output power of 0.7 W/mm with 30% efficiency at 18 GHz. Fujitsu reported a multiple-channel structure HEMT with 1.0 W output power, 3.1 dB gain, and 15.6% efficiency at 30 GHz for 0.5 um gate-length and 2.4 mm gate-periphery device.(30) At 35 GHz, a 2.4 mm device delivered 0.8 W with 2 dB gain 10.7% efficiency. TI also reported a multiple-channel structure which at 21 GHz achieved a power density of 1 W/mm with 3.9 dB gain and 26.6% power-added efficiency.(31) When tuned for maximum efficiency, this device achieved 5.4 dB gain and 0.9 W/mm with 30% efficiency. Later, TI reported a double-heterojunction doped-channel pseudomorphic power HEMT with a power density of 0.85 W/mm at 55 GHz 3.3 dB gain and 22.1% power-added efficiency.(32) This device had 0.2um gate length and the materials were prepared by MBE on Cr-doped substrates.

Although the power HBT is at an early stage of development, it has much potential power applications. Rockwell reported 0.4 W cw at 10 GHz with GaAlAs/GaAs HBT. This device displayed 48% power-added efficiency and 7 dB power gain.(33) Breakdown voltage of 23 volts was achieved in these devices. TI reported HBT devices with 4W/mm power density in pulse mode and 2 W/mm cw at 10 GHz.(34) In the cw mode, 80 mW power, 4 dB gain and 23% power-added efficiency were achieved. In the pulse mode, 160 mW power, 4 dB gain and 35% power-added efficiency were achieved.

4.2.2 DEVICE TECHNOLOGY

4.2.2.1 POWER MESFET

The MMIC technology using MESFETs is more mature and low-cost at present compared to HBT and HEMT technologies. At Ka-Band where the power MESFET can provide respectable power of about 1 watt for a discrete device, MMIC technology using GaAs MESFETs is very attractive. The current state-of-the-art for a power FET at 20 GHz is approximately 1 watt for a discrete device and approximately 250 milliwatts for an MMIC circuit. Consequently, the MESFET technology is a good candidate for developing Ka-Band power devices and amplifiers. From the MESFET data in Table 4-2(COMSAT VPE MESFET MMICs(25,26) and Fujitsu ion implanted MESFETs(27)), the MESFETs fabricated on VPE materials or ion-implanted substrates can meet the performance of power output and gain, but suffer from low power density (W/mm) and low power-added efficiency. However, when the

TABLE 4-2
POWER AMPLIFIER RESULTS REPORTED IN THE LITERATURE

Company	Device (Type, Lg)	Freq. (GHz)	Power (mW, W/mm)	Gain (dB)	Eff. (%)	Ft (GHz)	Fmax (GHz)
MESFET							
TI[1]	MBE FET, 0.25um	35	53, 0.71	5.2	34		
		35	45, 0.61	5.6	41		
COMSAT[2,3]	1 Stage Amp., 0.45um	28	481, 0.48	4.3	11.2		
	4 Stage Amp.	28	437, 0.44	18.9			
	1 Stage Amp.	50-56	95, 0.32	4	11 @ 55		
	4 Stage Amp.	50-56	85, 0.28	16.2			
Toshiba[4]	I^2 FET, 0.6um	29.5	500, 0.21	5.3	16		
		29.5[a]	1000, 0.42	3			
	Combined FET	29.5	1000, 0.21	4.2	11		
		29.5[a]	1600, 0.33	3			
HEMT							
GE[5]	HEMT, 0.25um	35	25, 0.49	5.7	42		
		35	30, 0.60	6.0	32		
		35[b]	104, 0.69	5.0	44		
		35[b]	132, 0.88	5.0	30		
		60	17, 0.33	3.0	28		
		60	22, 0.43	3.0	20		
		60[b]	85, 0.57	3.3	27		
		60[b]	100, 0.67	3.0	22		
		94	9, 0.18	3	12		
Cornell[6]	HEMT, 0.3um	18	70, 0.7	11.5	30	52	110
Fujitsu[7]	HEMT, 0.5um	35	800, 0.33	2	10.7		
		30	1000, 0.42	2	10.7		
TI[8,9]	HEMT, 0.4um	21	50, 1	3.9	26.6		
		21	45, 0.9	5.4	30		
	HEMT, 0.2um	55	42.5, 0.85	3.3	22.1		
HBT							
Rockwell	HBT[10]	10	400, 0.4	7	48	60	100
TI	HBT[11]	10	160, 4	4	35	25	20

a Saturated Power Measurements.
b Double Heterojunction results.

active layer is grown by MBE or potentially MOCVD, the electrons in the active layers are more confined and can provide higher power density and power added efficiency as demonstrated by the TI results.(24) When the electron confinement is combined with E-Beam Lithography (EBL), power MESFETs can easily meet the 30 and 44 GHz requirements. Despite the superior performance of power HEMTs and power HBTs, power MESFETs will play a major role in the lower frequency spectrum because of the simple and mature technology and the low cost of MESFET fabrication.

At present, there are several obstacles to producibility of power MESFETs:

1. Materials requiring MBE and MOCVD would have to overcome the repeatability and uniformity problems. (MOCVD is attractive in that it has higher throughput).

2. The process requires EBL, which has low throughput and high cost, and gate recess, which has non-uniformity and is difficult to control.

3. Reliability for the VPE and ion-implanted layers has been well documented but that for the AlGaAs buffer or active layers has yet to be studied.

The development of power MESFETs in the next decade is illustrated in Table 4-3. Initially, the power MESFET performance will continue to improve until 1991. At the same time, the materials growth techniques will continue to improve until 1993 with regard to control, repeatability and uniformity. In parallel with this development, the newly developed structures will be subjected to military and space standard tests to establish their reliability. When most of the MESFET structures become mature and established, the pilot lines will start to transfer the processes to production and in the process, simplify or improve the process. Some of these tasks will include using 3 or 4 inch wafers with MBE or MOCVD grown layers and automatic wafer processing.

4.2.2.2 POWER HEMT

Power HEMTs have exhibited comparable power density and power-added efficiency to MESFETs. The highest power densities and efficiencies at 35, 60 and 94 GHz had been achieved with pseudomorphic AlGaAs/InGaAs HEMTs by GE. The current densities are comparable to MESFETs. The power output and gain of a single heterojunction GaAs/InGaAs HEMT is comparable to a double heterojunction GaAs HEMT. The future trend (35) for HEMT will be shrinking transistor gate length to 0.1 um and using a lattice-matched InGaAs/InP heterostructure with higher electron velocity than the pseudomorphic InGaAs/GaAs heterostructure. A maximum frequency greater than 300 GHz will be achieved.

The obstacles to producibility of power HEMTs are similar to those of producibility of power MESFETs:

1. Material requiring MBE and MOCVD would have to overcome the repeatability and uniformity problems.

2. The process requires EBL, which has low throughput and high cost, and gate recess, which has non-uniformity and is difficult to control.

3. Reliability study of InGaAs HEMT has been limited. The generic issues are confinement of the high electron density to the 2 dimensional electron gas and the generation of electron and hole trap centers.

The expected development of power HEMTs in the next decade is shown in Table 4-3. Initially, the power HEMT performance will continue to improve until 1993. At the same time, the materials growth techniques will continue to improve until 1993 with regard to control, repeatability and uniformity. (This material improvement work will be the same as that for material improvement for MESFET or HBT). In parallel with this development, the newly developed structures will be subjected to military and space standard tests to establish their reliability. When most of the HEMT structures become mature and established, the pilot lines will start to transfer the processes to production and in the process, simplify or improve the process. Some of these tasks will include using 3 or 4 inch wafers with MBE or MOCVD grown layers and automatic wafer processing.

4.2.2.3 POWER HBT

Heterojunction Bipolar Transistors offer significant promise for use as microwave and millimeter power devices with high efficiency. The high breakdown voltage and high current density of HBTs can lead to high power operation with small chip areas. Power density as high as 4 W/mm with a power added efficiency close to 50 % has been demonstrated. Projected fmax values above 100 GHz and extrapolated ft values greater than 50 GHz have already been achieved.

The most significant difference between HBTs and FETs, except vertical FETs, is that the HBT has a vertical structure which decouples the close relationship of maximum operating voltage and current. Current state-of-the- art HBTs utilize one-micron emitter strips to achieve more than 50 GHz cut-off frequencies. With the same device width, HBTs give a current conducting area ten times greater than FETs. Since all the critical submicron features for HBTs are fabricated in the vertical dimension during epitaxy, lithography requirements are relaxed considerably as compared to MESFETs. HBTs are unique among potential millimeter-wave devices since they can be fabricated with conventional one- micron optical lithography. A second advantage over MESFETs is that HBTs are small enough that signal phase differences across the

TABLE 4-3
FUTURE DEVELOPMENT OF POWER MESFETS, HEMTS, AND HBTS FOR PRODUCTION

Development Tasks	1987-88	1989-90	1991-92	1993-94	1995-96	1997-98
Performance Improvement	X______	______	______X			
	X_ _ _	_ _ _	_ _ _	_ _ _X		
	X......	......	......	X		
Materials Improvement	X______	______	______	______X		
	X_ _ _	_ _ _	_ _ _	_ _ _X		
	X......	......	......	X		
Reliability	X______	______	______	______X		
	X_ _ _	_ _ _	_ _ _	_ _ _X		
	X......	......	......	......	X	
Yield Enhancement		X______	______	______	______X	
		X_ _ _	_ _ _	_ _ _	_ _ _	_ _ _X
		X......	......	......	......	X
Cost Reduction		X______	______	______	______	______X
		X_ _ _	_ _ _	_ _ _	_ _ _	_ _ _X
		X......	......	......	......	X

______________ MESFETs

_ _ _ _ _ _ HEMTs

.... HBTs

device do not significantly affect device performance. Compared to MESFETs operating at the same frequency, HBTs offer two to four times the power density and five to ten times the packing density. Similar to silicon bipolar transistors, HBTs are inherently power devices capabe of operating at much higher frequencies. The advantages and disadvantages of HBTs are summarized in Table 4-4. (36)

The future trend for HBT development will be improving the HBT frequency response by minimizing parasitic base resistance and base collector capacitance and by reducing base and collector transit times. The fully selfaligned device structure achieves the highest cut-off frequency. EBL will be used to define submicron emitters. A cut-off frequency as high as 150 GHz will be achieved.

Complementary HBTs have been fabricated on the same wafer with closely matched device characteristics. These complementary pairs will be used to fabricate higher power, high efficiency Class B push-pull linear amplifiers.

The obstacles to producibility of power HBTs are similiar to those of power MESFETs and HEMTs:

1. Materials requiring MBE and MOCVD would have to overcome the repeatability and uniformity problems.

2. The complex nonplanar process requires both n and p ohmic contact, multilayer metal and dielectric depositions, and selective side-wall controlled dry etching techniques.

3. Reliability study of HBT structures has been limited.

TABLE 4-4
ADVANTAGES AND DISADVANTAGES OF HBTS

ADVANTAGES	DISADVANTAGES
1. High f_t: The transit distances are established by epitaxial growth not by lithography.	1. Nonplanarity and complex device processing.
2. High current handling capability per unit chip area: The entire emitter area conducts current.	2. Heatsinking, due to the high power density.
3. High transconductance: Resulting from the direct control over current flow by the input voltage.	
4. Low output conductance and enormous voltage amplification factor.	
5. High breakdown voltage.	
6. Small signal phase differences between different devices	

The expected development of power HBTs in the next decade is shown in Table 4-32. Initially, the power HBT performance will continue to improve until 1993 with regard to control, repeatability and uniformity. (This material improvement work will be the same as that for material improvement for MESFET or HEMT). In parallel with this development, the newly developed structures will be subjected to military and space standard tests to establish their reliability. When most of the HBT structures become mature and established, the pilot lines will start to transfer the processes to production and in the process, simplify or improve the process. Some of these tasks will include using 3 or 4 inch wafers with MBE or MOCVD grown layers and automatic wafer processing.

4.2.3 SUMMARY - POWER DEVICES

The general performance, and advantages and disadvantages of power MESFETs, HEMTs, and HBTs are listed in Table 4-5. For the lower frequency range from 20 to 35 GHz, the power MESFET will still be the workhorse because of the simple and mature process technology and low cost. For the medium frequency range from 30 to 50 GHz, especially where efficiency is critical, power HEMT is attractive. From the performance standpoint, the power HBT shows the most potential at high frequency. However, considerable development is needed before HBT will be ready for production. In all three device structures, material uniformity and repeatability are necessary for high yield and reliability. In addition, these structures must be qualified according to the military or space standard for insertion into systems before production can proceed.

4.3 LOW NOISE DEVICES AND MMICS

During the past 15 years microwave MESFETs have rapidly come on to the scene and have become in recent years the device of choice for low noise amplifiers. More recently the High Electron Mobility Transistor (HEMT) and pseudomorphic HEMTs have shown superior performance to conventional FETs.

The HEMT is deceptively similar to the conventional FET. Figure 4-7 shows the profile of a HEMT. It is seen to differ from a FET in that a layer of AlGaAs is introduced and the GaAs layer is undoped. This results in the formation of a two-dimensional sheet of electrons at the AlGaAs/GaAs interface. The saturated velocity of the electrons in this layer is greater than in the conventional nGaAs so the gate length does not have to be so small for good low noise performance. In

C-2

TABLE 4-5
COMPARISON OF POWER MESFETS, HEMTS, AND HBTS

Category	MESFET	HEMT	HBT
Performance			
f_t (GHz)	Low	Medium	High
f_{max} (GHz)	Medium	High	Low
Power Density	Medium	Medium	High
Efficiency	Low	Medium	High
Breakdown	Medium	Medium	High
Advantages	Simple process	Relative simple process	Lax lithography
Disadvantages	-	-	Complex process
	Recess unif.	Recess unif.	-
	Critical lith.	Critical lith.	-
	Material unif.	Material unif.	Material unif.

addition because of the higher bandgap the AlGaAs can be more heavily doped without compromising the gate breakdown voltage. The result is that significantly better low noise performance has been achieved with HEMTs. Even better results have been reported for pseudomorphic HEMTs in which an additional layer of InGaAs is introduced. Figure 4-8 shows GE's comparison of FET and HEMT noise figures.(37)

The data of Figure 4-8 is device noise figure which is never attainable in a complete amplifier because it is not possible to achieve the optimum match over a band of frequencies and because real matching circuits have loss that is calibrated out of the device measurement. The difference between the device's capability and the actual amplifier performance becomes greater as the bandwidth is increased and is greater in an MMIC amplifier than in a hybrid MIC amplifier because of the lossier matching circuitry and because of the difficulty of achieving as optimum a match. Figure 4-9 shows a summary of reported results for FET based MMIC amplifiers, and Figure 4-10 shows comparable information for HEMT based MMIC amplifiers.(38) The use in MMICs of the HEMT and pseudomorphic HEMTs reported by GE should result in even better MMIC amplifier results.

The introduction of these improved devices into low noise MMICs for millimeter-wavelengths must be a high priority task. Noise figure has a high leverage in overall system performance. Particularly in an inter-satellite link, reducing the receiver noise figure is crucial since antenna size and transmitter power is limited. Some inter-satellite link systems studies have shown that a 3.5 dB noise figure is required.

The only limit on introducing these new devices in MMICs is the ability to grow these sophisticated materials with sufficient uniformity and quality at an affordable price, and to fabricate the sub-half-micron gate geometries with sufficient control to result in an acceptable yield of MMIC devices.

4.4 MMIC DESIGN METHODOLOGY

A major consideration in the use of MMIC technology for a particular application is the design cost, the non-recurring engineering, of developing a custom chip.

As discussed in Section 4.1, the recurring cost of producing chips in large quantities can be attractively low. A 3 inch diameter wafer is in principle capable of producing over 4000 one-millimeter square chips. Even if the yield of good devices is only 10%, if the wafer fabrication cost is $10,000, the cost per chip is only $25. The cost of development, not only in dollars but also in time, can be prohibitive. One design iteration, consisting of initial, electrical design, mask layout, mask fabrication, wafer fabrication, and DC and RF evaluation can easily consume 4-6 months and $50,000-$100,000. Attempts can be made to minimize the cost by including many different circuits on one mask set and by including variations of one circuit,

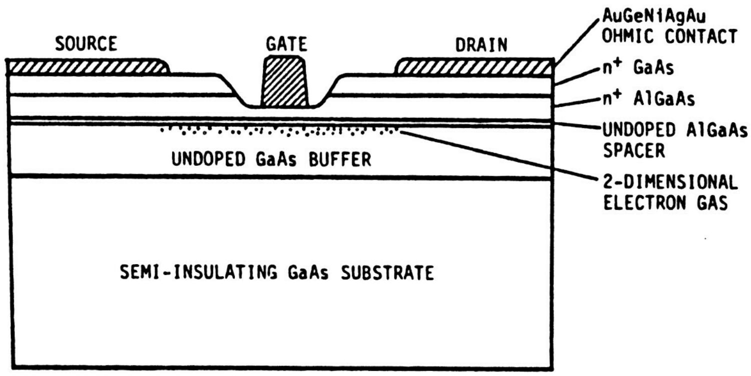


FIGURE 4-7 Profile of a High Electron Mobility Transistor (HEMT)

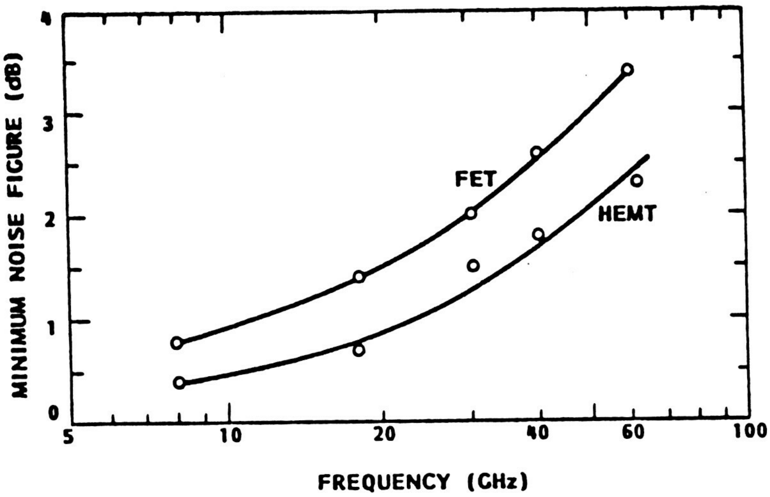


FIGURE 4-8 Comparison of HEMT and FET Noise Figures

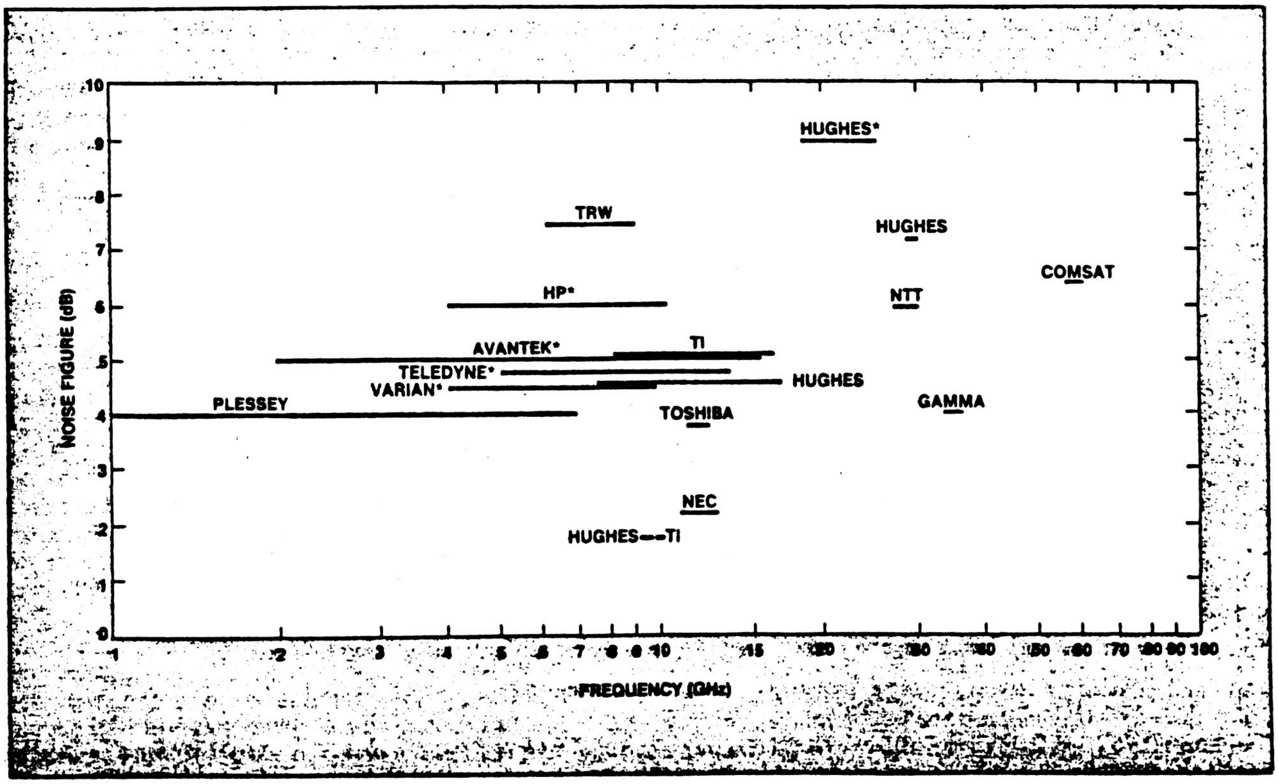


FIGURE 4-9 Summary of Reported Results for FET-Based MMIC Amplifiers

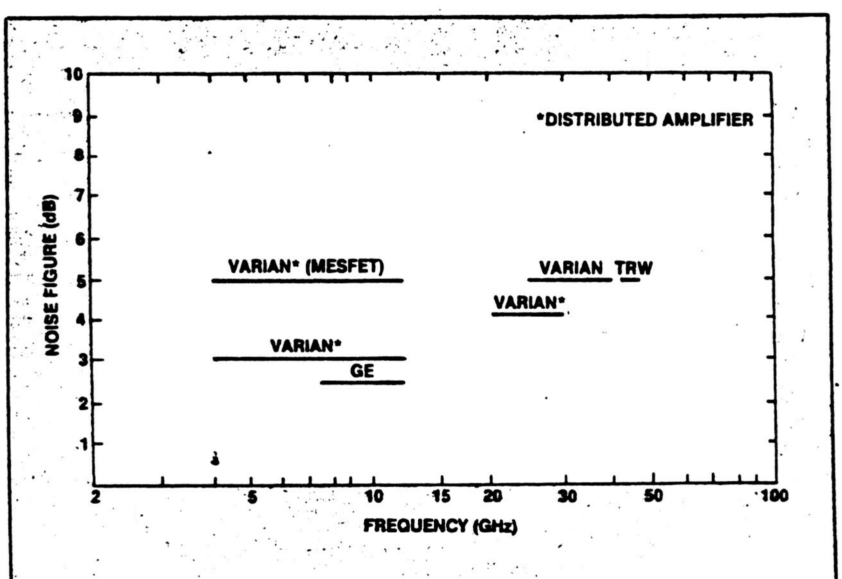


FIGURE 4-10 Summary of Reported Results for HEMT-Based MMIC Amplifiers

ASMMIC DESIGN PROCESS USES SINGLE GaAs FOOTPRINT FOR MANY APPLICATIONS

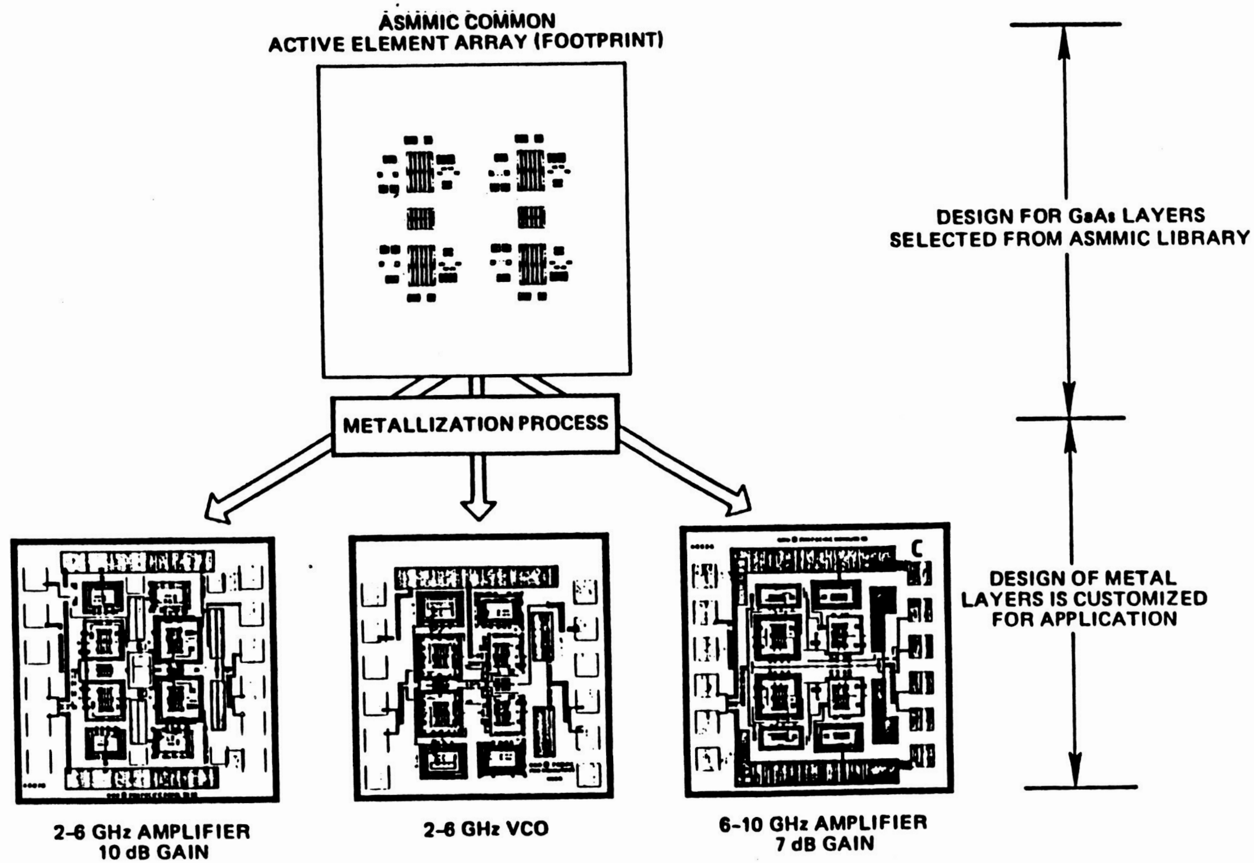


FIGURE 4-11 Example of Three Different Chip Designs Realized From One Footprint Using ASMMIC Approach.

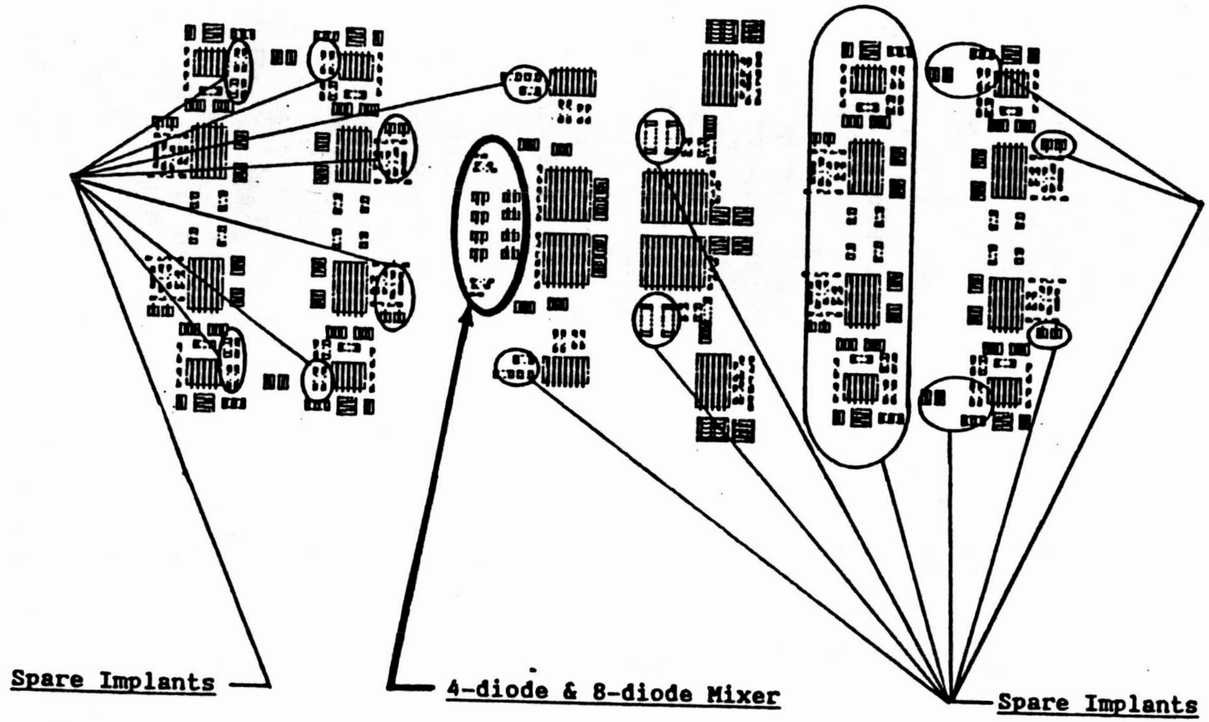


FIGURE 4-12 2 - 10 GHz ASMMIC footprint. Spare implants enable the footprint to be used for a wide variety of circuit variations.

varying critical element values for which there is some design uncertainty. The wafer shown in Figure 1-4, for example, was made froman R&D mask set which included 54 different circuits. Even if these steps are taken, however, unless the application requires a very large production quantity or unless the application has a critical need for the size reduction offered by MMIC, the MMIC development effort may not be justified.

A very important need, if MMICs are to be used in any but large quantity applications, is to develop techniques to reduce the cost and time of custom MMIC development.

Some important strides have been made in this direction as foundries have improved and expanded their computerized libraries of design information and device models, to complement the established CAD tools such as SUPERCOMPACT, TOUCHSTONE, and SPICE. Some newer programs such as LIBRA, using harmonic balance, should improve the capability for handling non-linear elements.

In addition, improvements in on-wafer microwave probing techniques make possible better RF characterization of active and passive circuit elements through 50 GHz. The RF probing makes it much more practical to obtain data on uniformity and parameter distributions so that designs can be made taking in to account anticipated variations.

It is important, and to be anticipated, that the next ten years will bring improvements in CAD techniques, particularly for non-linear circuits and for interactions in densely packed circuits, and in on-wafer testing techniques.

However, another promising technique, along somewhat different lines, but directed specifically at the problem of reducing MMIC development costs for small and medium quantity applications, is the Application Specific MMIC (ASMMIC). This technique is the outgrowth of R&D performed by Ford Aerospace and by the Ford Aerospace Phase 0 MIMIC Team.

ASMMIC promises to simplify the development process and hence reduce the development cost and risk. Furthermore ASMMIC can realize volume production savings through a shared production process and through increased production demand. The foundation of the ASMMIC concept is a predesigned footprint building block. This footprint comprises the layers containing FETs, resistors and diodes in an array compatible with a wide variety of circuit functions. The chip is completed by applying personalized metalization to the footprint. This is illustrated in Figure 4-11. This figure illustrates a basic footprint being used for three different applications by applying the proper metalization pattern. With a library of a few basic footprints it will be possible to meet a large number of MMIC requirements through appropriate specialization.

Figure 4-12 shows another example, a 2-10 GHz footprint. The spare implants enable the use of the same footprint for many applications. The usefulness of the technique has been demonstrated even at millimeter-wavelengths. Figure 4-13 shows a millimeter-wavelength footprint personalized as either a 27 GHz narrowband amplifier or a 30 GHz wideband amplifier. Wafers of footprints can be produced in volume, fully characterized, and placed in inventory. The characterized data will be used as accurate para- meters of the models contained in the ASMMIC CAD library. The ASMMIC CAD will facilitate the design of the metalization layers which establish the circuit functionality (amplifier, mixer, oscillator, limiter, switch, etc) and the operating frequency. The design and application of the metalization layers can be accomplished with high confidence and within a time span of a few weeks.

Table 4-6 summarizes the advantages of the ASMMIC approach. Figure 4-14 is an estimate of the cost advantages of the approach showing in particular its advantage for low quantity applications which are typical of space requirements.

4.5 HYBRID MIC TECHNOLOGY

Hybrid MIC technology is the primary competing technology to the Monolithic MIC approach. It is the technology MMIC technology is being developed to replace. Hybrid MIC technology has evolved over the past 20 years. It is characterized by the fact that the active devices are on separate chips from the passive circuitry which is typically on a ceramic substrate such as alumina.

Figure 1-2 showed a photograph of a hybrid MIC two-stage amplifier. This represents the state-of-the-art of hybrid circuitry. In this amplifier the active devices are dual-gate FETs which are in unpackaged, chip form to eliminate package parasitics and to minimize the effects of interconnections. The capacitors are chips soldered to the metalization on the alumina substrates. The resistors in this case are formed from thin film tantalum nitride metalization deposited directly on the substrate, although in many hybrid circuits the resistors, too, are chips soldered to the circuit. In the case of the amplifier of Figure 1-2, since the FETs are unpackaged the entire circuit module must be hermetically sealed.

The major deficiencies of the hybrid approach are:

1. Large amounts of skilled, hands-on assembly time are required which keeps the cost high even in large quantity production.
2. The parasitic reactances associated with the interconnections limit the performance and cause unit-to-unit variations which must be tuned out by skilled technicians

3. The hybrid circuits can not be made as small as the MMIC versions.

The effects of the interconnection parasitics are the most fundamental and they become rapidly more serious as frequency is increased. Figure 4-15 shows the calculated reactance of a bond wire as a function of frequency for two different wire lengths. At millimeter-wavelengths the reactance becomes a very significant circuit element. Unfortunately the effect of this circuit element is usually to limit the achievable performance. But, equally important, assembly techniques are not adequate to maintain tolerances which will keep assembly variations from affecting performance, with the result that much skilled technician time is required to tune out the effects of assembly variations. Although improvements in hybrid production and assembly equipment, such as automated wire bonding stations, will make some improvements in hybrid capability in the next few years, it is felt that the hybrid technology after over 20 years of development is reaching a plateau where significant improvements can not be anticipated, particularly for circuits above 20 GHz.

4.6 PHOTONICS

4.6.1 INTRODUCTION

The advantages of phased array antenna systems for microwave and millimeter wave applications are now well known. The requirement of phase array systems for large number of active electronic components has accelerated development of relatively low cost monolithic microwave integrated circuits (MMICs). A remaining requirement for phased array systems is development of effective means for distribution of rf and control signals within the array. In general, there is a requirement to integrate the various constituents of the array into a compact, high performance, and cost effective whole. Various phased array architectures have been proposed to accomplish the task. The use of optical means to distribute rf and control signals in phased arrays systems has been discussed previously (39,40,41,42,43,44) More recently, new optical control techniques for phased arrays systems have also been proposed. (45,46)

In this report, the photonic device and subsystem technology requirements for application to phased array systems are examined. First the issues relevant to applying photonic devices and subsystems to phased arrays are discussed. Then the advantages and disadvantages of using photonics technology in phased array systems are pointed out. Next, photonic device and subsystem technology applicable to phased array systems is reviewed. Finally, the key technology requirements for applying technology to phased array systems and areas for further development are identified.

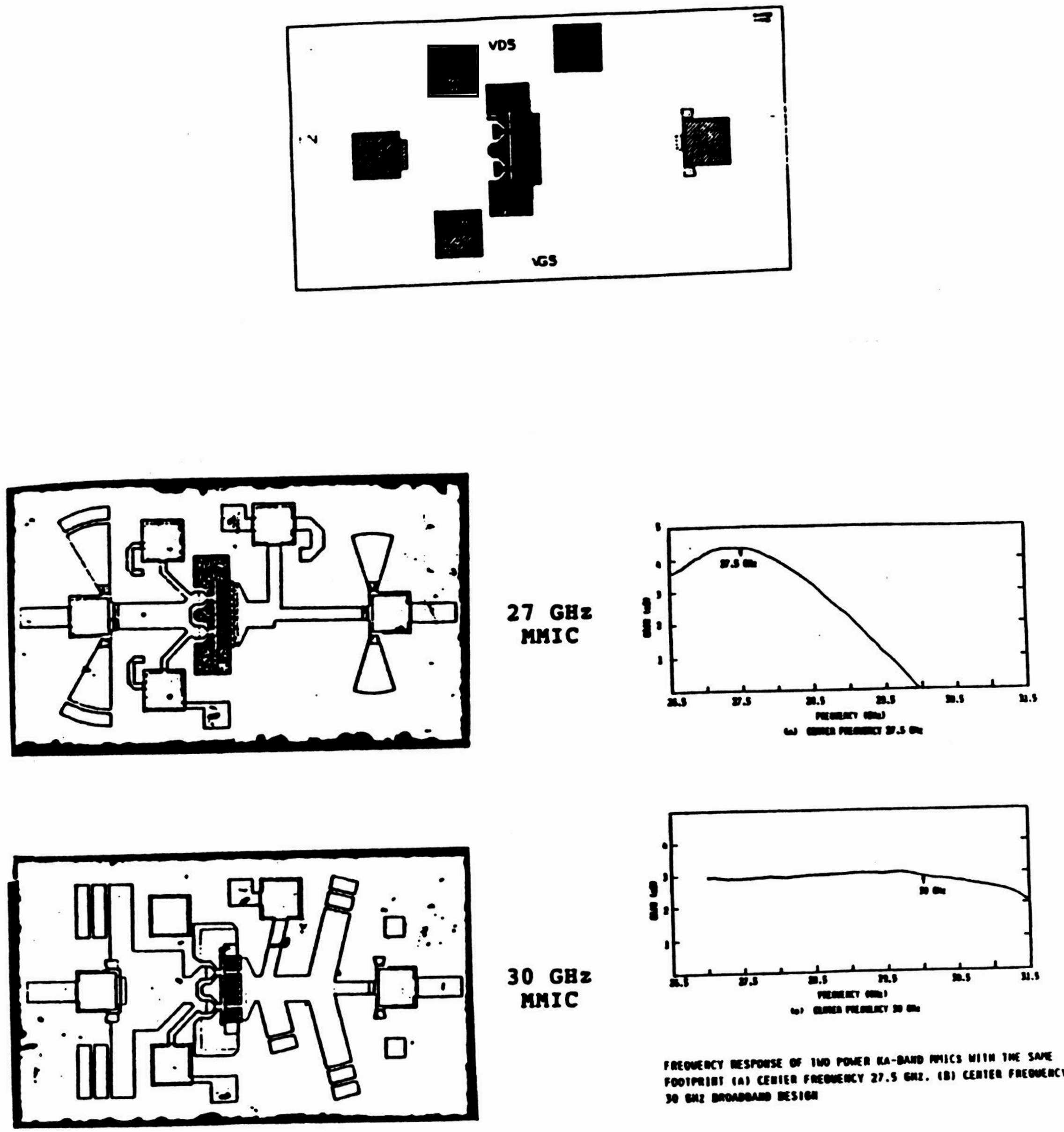


FIGURE 4-13 A millimeter wave ASMMIC footprint has been personalized resulting in a 27 GHz narrowband and a 30 GHz wideband amplifier

Table 4-6

ASMMIC ADVANTAGES vs. CUSTOM MMIC

- Early MMIC systems insertions
- Greater affordability to user
- Accessible to small volume users
- Can be designed by a broad group of engineers
- Large development cost savings
  $40 - 80K for ASMMIC
  $80 - 200K for custom MMIC
- User control of proprietary and classified designs
- Adaptability allows inexpensive system changes
- Transportability of design, process, material characteristics across design centers and foundries

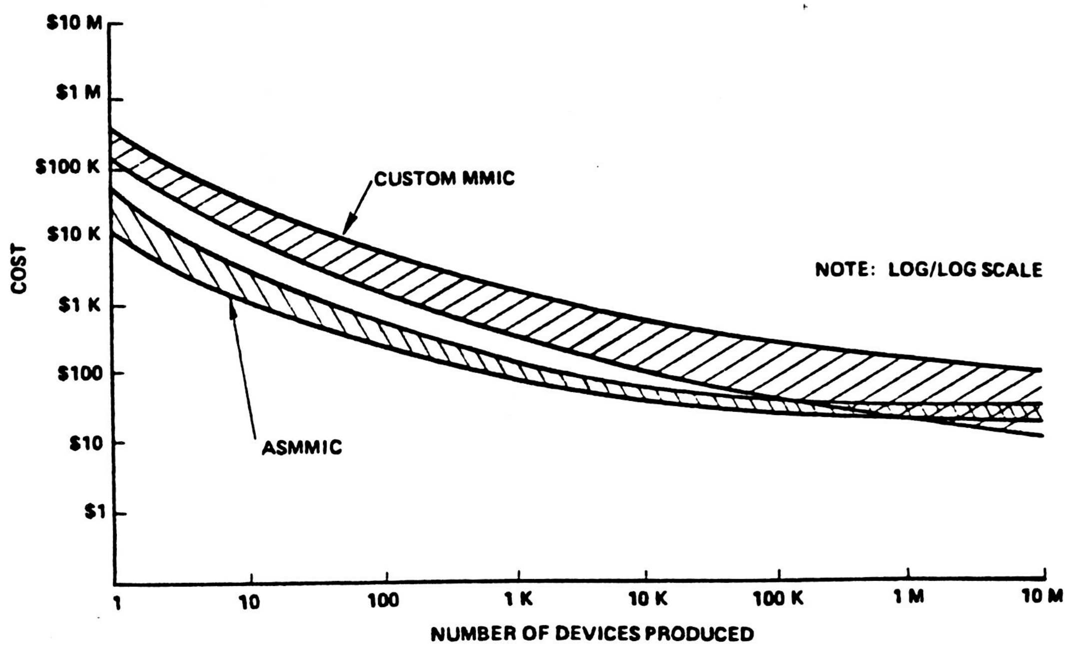


FIGURE 4-14 Cost Advantages of the ASMMIC Approach

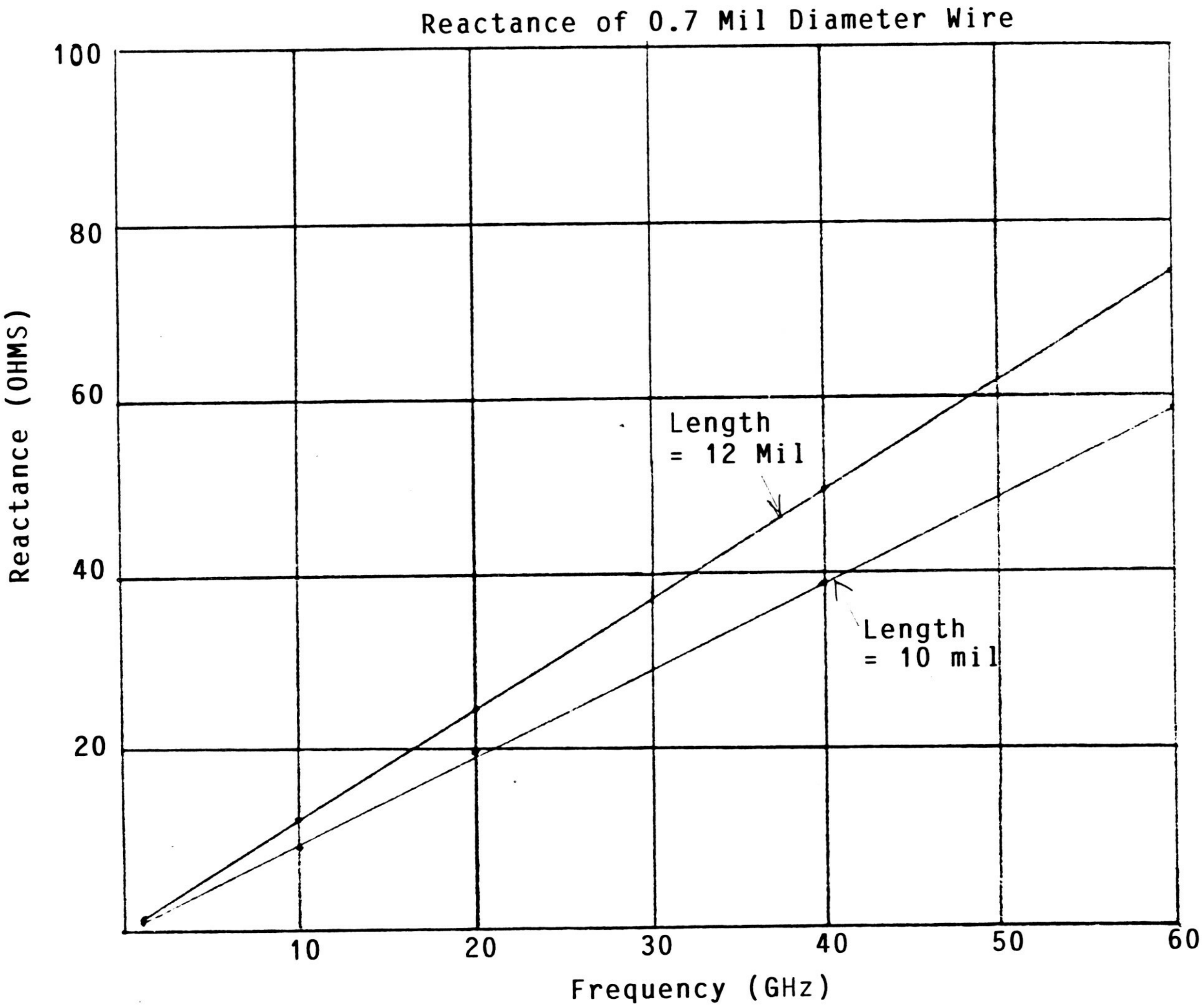


FIGURE 4-15 Bond Wire Reactance as a Function of Frequency

4.6.2 PHOTONIC TECHNOLOGY FOR PHASED ARRAY APPLICATIONS

4.6.2.1 ISSUES

Many conventional approaches to phased array system implementation result in expensive, heavy, and high loss systems. However, the integrated circuits (MMICs) promise to address several of these issues. MMICs for phased array applications offer potentially lower cost, lighter weight, lower loss and more compact systems which exhibit more graceful degradation characteristics. Notwithstanding the progress made to date in the development of MMICs, the system presents a formidable task. Optical signal distribution techniques employing well-developed optical fiber technology may offer a practical solution to this difficult interconnection problem.

4.6.2.2 ADVANTAGES AND DISADVANTAGES

The advantages of using optical fibers for phased array interconnection include their wide bandwidths, low loss, light weight mechanical flexibility, minimum crosstalk, and low susceptibility to electromagnetic interference (EMI). Optical fiber signal distribution technology is also mature and available today. The maturity of optical fiber as a signal distribution medium is well demonstrated by the widespread application of optical fiber for data communications demanding reliability requirements such as transoceanic submarine cable systems. On the other hand, merging MMIC technology and fiber optics into an effective phased array system design will require further development. For example, it will be necessary to develop the optoelectronic interface between the MMIC and fiber. Fortunately, the semiconductor materials and fabrication technology for optoelectronic devices on the same chip, or within the same subsystem module, is a feasible undertaking. Moreover, there are many parallel performance and economic drivers for photonic-electronic device integration which are active in the data communications and telecommunications industries. Therefore, we can expect relatively rapid development progress in photonic-electronic integration.

4.6.2.3 APPLICABLE PHOTONIC TECHNOLOGY

Photonic technology applicable to phased array systems includes optical fibers, connectors, and a number of active photonic devices. Optical fibers and associated hardware, such as connectors, splices, couplers, etc., are well developed today owing to their extensive use in the data communications and telecommunications industries. The active photonic devices of interest for use in phased array systems include semiconductor lasers, semiconductor photodetectors, wideband optical modulators, and means to integrate these device types with active electronic devices and MMICs. All of these photonic devices and ICs have been under intense development in the last few years. This intense photonic component development has been prompted most directly by the need to deliver components for use in the large number of fiberoptic data communications and telecommunications

systems installed in recent years. Photonic technology for microwave systems is required to operate at much higher frequencies (8 -44 GHz) than is typical of todays communication system requirements. nevertheless, more recent photonic technology developments are aimed at ever increasing frequencies. For example, direct digital modulation of semiconductor laser at 16 Gb/s has been demonstrated.(47) Direct modulation of a semiconductor laster is attractive owing to the relative simplicity of modulating the laser by directly modulating the drive current to the laser. Direct microwave modulation of semiconductor lasers with small signal bandwidths exceeding 22 GHz has also been reported(48), and is illustrated in Figure 4-16. Theoretical predictions of still higher frequency direct laser modulation using multiquantum well lasers have now been verified. The achievement of direct modulation band- widths in the 30-45 GHz range will require development of laser structures incorporating multiquantum well active regions and low parasitic capacitance designs. Table 4-7 shows a ten year prediction of the small signal direct modulation bandwidth for semiconductor lasers. Note in Table 4-7 the relatively rapid initial progress expected as modulation bandwidths are increased to the 40 GHz range. After these initial improvements from the 20 to 40 GHz range are achieved, more gradual improvement is expected as fundamental limits are reached.

TABLE 4-7
PROJECTION OF SEMICONDUCTOR LASER DIRECT MODULATION BANDWIDTH BY YEAR

YEAR	1988	1990	1992	1994	1996	1998
MODULATION BANDWIDTH	22 GHz	32 GHz	42 GHz	45 GHz	50 GHz	52 GHz

Although direct modulation of a semiconductor laser is attractive in its simplicity, as bandwidth requirements increase, the use of external optical modulators become advantageous.(49) In an externally modulated semiconductor laser, the laser is operated as a continuous wave source of optical radiation. The output of the laser is then directed to a separate optical modulator such as a waveguide electroopical modulator.(49) The use of an external modulator is appropriate when the direct modulation bandwidth of the laser is exceeded, or when the wavelength chirp induced by direct laser modulation is unacceptable. Modulators with bandwidths greater than 20 GHz have already been demonstrated. for example, a GaAs traveling-wave electrooptic waveguide modulator with bandwidth greater than 20 GHz (see Figure 4-17) has been reported.(50) Electrooptic modulators with bandwidths exceeding 100 GHz may also be feasible.(51,49)

In an optical signal distribution system it is, of course, also necessary to detect the modulated optical signal. Photodetectors with the required signal bandwidth have already been demonstrated. For example, PIN photodiodes fabricates using MMIC-like techniques (airbridge interconnects) with bandwidths of 35 GHz have been

reported.(52) Even faster metal-semiconductor-metal (MSM) photodiodes with pulse response characteristics corresponding to a photodetector bandwidth of 105 GHz have also been reported. (53) The primary remaining challenge for photodetector development is the realization of very wide bandwidth detectors with high sensitivity which are compatible with MMIC monolithic integration technology.

Yet another requirement for the use of photonic technology in phased array systems is to integrate the photonic MMIC componentry into operating subsystems and systems. Most of todays commercially viable photonic component and subsystem technology is based on hybrid integration of photonic and electronic devices. That is, discrete photonic devices are combined with discrete or integrated circuit electronic devices in a hybrid packaging approach to fabricate subsystem modules. For microwave and millimeter wave applications, it will probably be necessary to monolithically integrate photonic and electronic devices so as to obtain adequate high frequency performance.(54) Monolithic integration of photonic and electronic devices is an ongoing area of research and development at this time. Rapid progress during the next ten year period can be expected. Just as for the case of MMICs for phased array applications, systems requirements for cost, speed, size, weight and manufacturability are the driving requirements for monolithic integration of photonic and electronic devices.

4.6.2.4 KEY TECHNOLOGY REQUIREMENTS

Long term successful development of phased array systems incorporating photonic technology will require several key technology developments. Several of these will be identified here. Semiconductor laser development targeted at ultralow threshold current operation (55,56), increased power output, and improved modulation bandwidth will be required. Ultralow threshold operation and increased laser power output will be necessary to minimize the power requirement in large scale array systems. The development of external laser modulators will provide an alternative to direct laser modulation, and may be expected to offer still higher laser modulation bandwidth when fundamental limits of direct laser modulation are reached. Continued development of high speed photodetectors will also be required. A major thrust from the present point on should be the development of practical photonic-electronic integration approaches. Identification of specific phased array system configurations and requirements which would benefit from, and be suitable for, integration of photonic and MMIC devices would provide a useful focus. The advantages of MMICs integrated with photonic devices (Monolithic Microwave and Photonic Integrated Circuits - MMPICs) would address phased array system requirements for speed, cost, size, weight, and manufacturability. As the technology for MMPICs and the specific design of phased array subsystem modules advances, development effort to assure the reliability of the components and subsystems will be required. Finally, photonic technology should not be considered solely as a replacement for coax and waveguide as a signal transmission medium

which offers reduced weight, size, etc. Rather, novel approaches, methods and design techniques made possible through application of photonic technology should also be considered (see for example 45 and 46). In short, there is the potential for considerable innovation in the application of photonic technology to phased array systems.

4.6.3 SUMMARY AND CONCLUSIONS

Photonic technology for microwave and millimeter wave phased array systems has been described. The issues relevant to phased array applications of photonic technology have been identified, and the advantages and disadvantages of using photonic technology in phased array systems have been discussed. The photonic device and subsystem technology applicable to phased array systems has also been reviewed. Finally the key technology requirements for applying photonic technology to phased array systems was described and areas for further development were identified.

Several conclusions can be drawn from the study. Photonic technology is attractive for use as a means of distributing rf and control signals in phased arrays due to the unique properties of the interconnection medium: optical fiber. Optical fiber technology is mature and is in widespread spread commercial and government use today. Photonic device technology is developed today to the point that discrete optoelectronic devices such as semiconductor laser and photodetectors, are in general use. Moreover, discrete optoelectronic devices are also used today in applications requiring extreme device reliability. For application to phased array systems, further work to merge MMIC and photonic technology is required. The microwave performance of photonic devices is improving rapidly as a result of continuing development. In particular, the level of integration required for monolithic microwave and photonic integrated circuits (MMPICs) needs to be examined. Phased array system architectures incorporating photonic technology need to be defined so that the required level of MMPIC integration and component performance can be determined. Finally, novel approaches, methods and design techniques made possible through applications of photonic technology should provide for considerable innovation in phased array systems design.

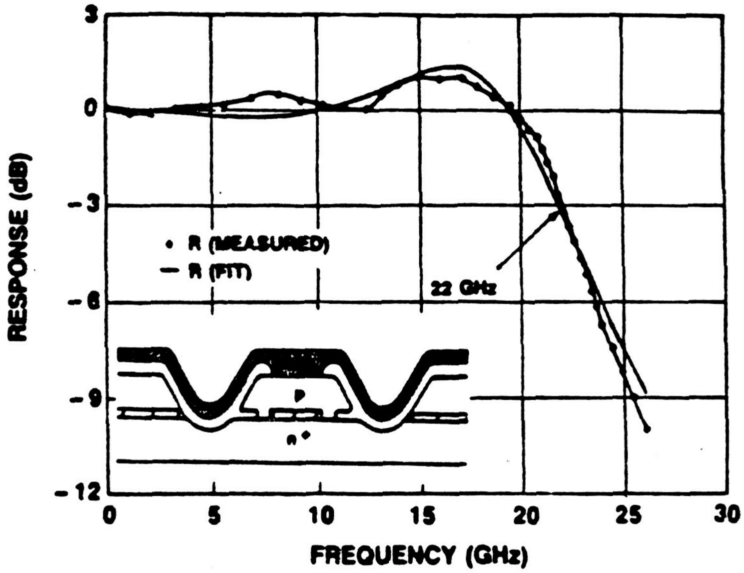


FIGURE 4-16 22 GHz Laser Small Signal Direct Modulation Bandwidth (after Olshanskss, 1988)

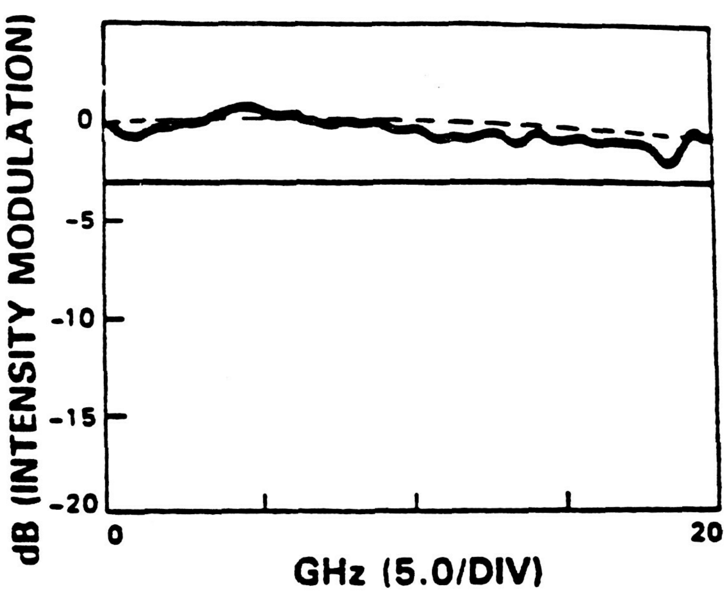


FIGURE 4-17 Frequency Response of a GaAs Traveling-wave Polarization Electrooptic Waveguide Modulator with Bandwidth Greater than 20 GHz (after Wang, 1987)

5.0 ASSESSSMENT OF POTENTIAL MMIC APPLICATIONS

Section 3.0 identified a number of potential space applications of MMICs.
These can be summarized as follows:

a. 32 GHz transmit modules for feed arrays and phased arrays on JPL probes.

b. C-band modules for use in JPL synthetic aperture radar for Mission to Planet Earth.

c. Modules for electronically steerable multibeam antenna for control zone communication for space station.

d. Phase shifters for on-board beam forming for TDRSS.

e. Bulk demodulators for numerous communication satellite applications including Data Distribution Satellite.

f. Transmit modules for active arrays at 20 and 60 GHz and receive modules for 30, 44, and 60 GHz.

g. IF and baseband switch matrices.

h. Interface between MMIC and optic control or signal distribution.

i. Use in conventional transponders to reduce size and weight and to improve reliability.

The key performance requirements for these applications are indicated in Table 5-1.

To assess the benefits of possible development programs focused on these applications requires the consideration of a number of factors including the following:

a. Benefits resulting from successful development program. The benefits can take several forms:

  - May make a mission possible which otherwise would not be possible

  - An economic benefit, ie the development is cost effective in the sense that the development cost can be recovered through cost savings resulting from the development

  - Improvement in system performance

b. Possible commonality- the development would impact several applications

c. Cost and difficulty of the proposed development

d. Likelihood of success, degree of risk

e. Likelihood that the technology would be developed without NASA support: would it be developed by the military or by private industry?

f. Timing of the requirement

It must be recognized that the assessment of benefits is not a straight-forward, objective task when the benefits are as disparate as those which would result from the developments of Table 5-1. Some are readily quantifiable in economic terms. Some are not.

For instance, the study of the channel amplifier showed that an MMIC version in an advanced modern communication satellite transponder could save 11.3 kg of mass. Using the well established factor of $50,000 per kilogram to translate mass savings in geostationary orbit to cost savings, leads to the conclusion that a savings of $560,000 per flight would result from weight savings alone. In addition, the recurring costs of the MMIC version should be less than that of the hybrid MIC version, so that it is estimated that the nonrecurring development cost could be recovered on the first satellite using the MMIC channel driver, with substantial savings on further flights.

A similar analysis was made of the benefits of on board beamforming using MMIC phase shifters versus hybrid MIC phase shifters. There it was shown that the mass savings of the MMIC approach would make it $1.2 M less expensive to implement per flight than the MIC version. This is in addition to the savings resulting from expected lower recurring costs for producing the MMIC phase shifters in the quantities assumed.

In the case of the X-Band beam forming network, this study showed that a proposed MMIC realization would weigh only 24 pounds compared with the 125 pounds of a waveguide beam forming network using ferrite phase shifters and variable power dividers. Using the $50,000 per kilogram factor this implies a savings of $2.3 M per flight as a result of the weight reduction.

A Ford Aerospace study performed for NASA-Lewis concluded that a bulk demodulator using digital GaAs technology would have substantial mass and power advantages over a CMOS VLSI approach. For the advanced satellite studied, a satellite which would be a candidate for a NASA Data Distribution Satellite, the study predicts a mass saving of about 64 kg and a power savings of over 1000 Watts using the projected 1995 GaAs technology.

TABLE 5-1

KEY PERFORMANCE REQUIREMENTS OF MMIC APPLICATIONS

APPLICATION	SOURCE OF REQUIREMENT	KEY PERFORMANCE REQUIREMENTS
Interplanetary Probes (eg Cassini and Mars Sample Return)	JPL	32 GHz power amplifiers (100 mW, > 30% efficiency), phase shifters and variable gain amplifiers for active arrays
Synthetic Aperture Radar (Mission to Planet Earth)	JPL	5.3 GHz four-bit phase shifter and small signal amplifier (Long term: power amplifier with 12 W peak, 1 W avg; low noise amplifier with 1.5 dB noise figure)
Space Station (Control Zone Comm.)	Johnson Space Center	21-23 GHz power amplifiers, 2 W, 15 dB gain, 30 % efficiency
TDRSS (On board beam forming)	Ford Aerospace and Goddard Space Flight Center	2.29 GHz narrowband five-bit phase shifter
Future Commercial, Military and NASA Communication Satellites (eg NASA Data Distribution Satellite)	Ford Aerospace	Bulk demodulator, eg 400 channels, 72 kbit/sec IF switch matrices (100 X 100)
Downlink Multi-scanning beam antenna	NASA-Lewis	Transmitter modules, 17.7-20.2 GHz, 200 mW, 15 % efficiency, 16 dB gain. Phase shifter, 5 bits Variable power, 0 to 0.5 W, 6 to 15 % efficiency, 4-bit control
Uplink Multi-scanning-beam antenna	NASA-Lewis	Receiver modules, 27.5-30 GHz, 5 dB noise figure, 30 dB RF/IF gain, 5-bit phase control, 4-bit gain control

TABLE 5-1

KEY PERFORMANCE REQUIREMENTS OF MMIC APPLICATIONS
(continued)

APPLICATION	SOURCE OF REQUIREMENT	KEY PERFORMANCE REQUIREMENTS
Intersatellite link active array	Military	60 GHz power amplifiers, low noise amplifiers, digital phase shifters, variable gain amplifiers
Anti-jam antenna	Military	7.9-8.4 GHz amplifer, 2.5 dB noise figure, 20 dB gain, 5-bit phase shifter and variable gain amplifier
Transponder Channel Amplifier	Ford Aerospace	12.25-12.75 GHz, 45 dB max gain, 21 dB gain variation commandable in 3 dB steps, 7 dB noise figure

For the interplanetary mission applications, JPL has made thorough analyses of the advantages of using 32 GHz rather than X-Band. They have made extensive studies of how the 8 dB advantage of 32 GHz over X-Band could be translated in to benefits for missions such as the Cassini Probe and Mars Sample Return. JPL studies project, for instance, that a 25 Watt RTG could be eliminated from the Cassini probe at a savings of $5M, overcoming a projected $3.4M increase in the recurring cost of the 32 GHz array. They estimate a non- recurring development cost of $7M.

Benefits for the Mars mission are substantial but not so easily quantifiable. The JPL study considered both the use of flat planar arrays and TWTA fed parabolas at both X-Band and 32 GHz, using both 70 and 34 meter receiving systems. In all cases 32 GHz demonstrated a clear mass advantage over X-Band, on the order of a factor of two. Between the two 32 GHz approaches, the flat planar array has substantial size advantages over the parabola and TWTA approach.

Thus, to a limited extent and in some applications it is possible to express MMIC benefits and costs in terms of dollars, and in this way to reach a conclusion about the advisability of pursuing the monolithic approach. This tends to be the case in the more immediate, more straightforward applications where the benefits can be calculated easily in monetary terms. The channel amplifier is an example of this class. The decision of whether to proceed with the MMIC approach can be based on whether the savings exceed the development costs. No new

capabilities or intangible benefits would appear to be promised by the development.

The benefits in applications such as the space station and interplanetary probes are not so easily summarized in monetary terms. An initial space control zone communication capability can be established using omni antennas for close in communication and one, or more, steerable directional antennas for more distant users. But an approach using multibeam active arrays not only will consume less space and not be dependent on mechanical steering mechanisms, but more importantly will have far greater potential for expanding to handle more users and activity, as would be demanded, for example, if the space station is to be used as an assembly station or a fueling depot, as for the Humans to Mars Initiative of the Ride Report.

Similarly, TDRSS can operate with beam forming accomplished on the ground as it is currently designed to do. This approach limits the capacity of the system, however, and is subject to possible performance limitations. On board beam forming appears to have far greater potential for future expansion. Although it is possible to quantify the advantage of an MMIC approach to on board beam forming over a hybrid approach, as was done on this contract, the benefit of on board versus off board beam forming is more difficult to quantify.

Several of the applications of Table 5-1 are for future communication satellite systems, to accommodate VSATs and to serve as stepping stones to the capability for personal access to the communication satellite system. The technologies for on board signal processing, such as bulk demodulators and switch matrices, and for scanning multi-beam arrays fall into this category. Such a capability to provide convenient, low cost access from small, personal terminals to a world wide digital communication network can have clear economic and social benefits. However, it is difficult to weigh this benefit rationally against the also clear benefits of technologies devoted to space exploration and to taking man into space.

Fortunately, the difficulty of weighing different categories of benefits against one another may not be as serious as it might seem. When the applications of Table 5-1 are studied from the point of view of common technologies rather than competing applications, it is seen that there is a great deal of commonality which suggests some clear technical directions.

Clearly a "cutting edge" technology is efficient power amplifiers for frequencies from 20 to 60 GHz. Developing power amplifier technology with this capability is the key to transmitters for interplanetary probes, to power amplifiers for active arrays on the space station, to scanning multibeam downlinks for advanced communication satellites, and to transmitter arrays for intersatellite links.

Together with the efficient power amplifier capability, this set of

applications requires the monolithic phase shifters and variable gain amplifiers needed for active arrays. Fiber optic control circuitry may be required in some applications for signal distribution and control. This same technology development with the addition of low noise amplifiers at 30, 44 and 60 GHz would support also the need for uplink receive arrays and intersatellite link receive arrays.

Thus a broad category of applications can be supported by the development of this 20-60 GHz MMIC based active array technology. A good foundation has already been laid in this technology through development sponsored by NASA and the Air Force. As a result of this work much of the required development can be regarded as low risk. Recent laboratory results from GE and Texas Instruments on power HEMTs show efficiencies in the desired range in the 30 GHz region. For example, GE has reported 132 milliwatts at 35 GHz with 30% power added efficiency.

To date the power device performance closest to that required has been obtained from power HEMTs. An important element of risk is that the reliability of this approach has not been established. Heterojunction Bipolar Transistors (HBTs) have shown significant promise for efficient high power devices. However, to date these results have been only at lower frequencies, for example Rockwell's reported 400 milliwatts at 48% efficiency at 10 GHz and TI's 160 milliwatts at 35% efficiency also at 10 GHz. The HBT approach would seem to have great promise for efficient power devices in the 20-60 GHz range. Thus, to reduce risk, power HBT technology should be developed as a backup to the power HEMT approach.

Although much work has been done on MMICs for millimeter-wavelength active arrays, additional work is required to support the many applications for such arrays. In particular the digital phase shifters reported to date show large variation in insertion loss as the phase setting is changed, and the magnitude of this problem varies from unit to unit. This is a serious problem in an array application. In principle it is possible to compensate by changing the associated variable gain element when the phase is changed. This places a large additional burden on the control circuitry, however, and in some applications the control circuitry is already becoming a important contributor to the weight and power consumption of the system. In principle this insertion loss variation can be reduced to a very small value by more sophisticated design. This development would have important benefit.

The backplate technology, the technology for integrating the MMIC modules to the radiating elements and distributing the control and RF signals to the elements, is an important technology area which needs more development to support all of these array applications

This millimeter-wavelength active array development is clearly beneficial because it serves so many of the identified applications of Table 5-1. By the same token it benefits many possible users such as

NASA, the military, and commercial satellite communications. Thus the development should be coordinated and supported by all the potential beneficiaries. This requires close coordination of NASA, the Air Force, and private industry to avoid needless duplication of effort while maintaining the advantages of pursuing competing approaches.

Some important applications of Table 5-1, however, are not encompassed by the development of millimeter-wavelength active array development. In particular, the phase shifter for on board beam forming seems to be a very important and beneficial application. The requirement seems to be within the capability of the state-of-the-art and, hence, entails only low risk. It requires a custom MMIC chip which will not be developed as a generic part by an MMIC vendor, nor will it be developed for some other application. The successful development of the phase shifter would help establish the credibility of MMICs as a useful component for space circuitry. Therefore, this appears to be a very attractive component for NASA funded focused development.

The MMIC module for the C-Band synthetic aperture radar for the Mission to Planet Earth is another beneficial MMIC circuit which is not encompassed by the millimeter-wavelength array efforts. The development of the digital phase shifter and the low power gain stages would make a major contribution to the solution of the problem of reducing the weight of the radar. Yet the development of these circuits should be within the capability of present technology. The development of this chip would serve the important function of establishing MMIC technology as a credible contributor to the needs of space based synthetic aperture radars. A more ambitious program would tackle the power output stages and the low noise preamplifier where the requirements are a greater challenge to the technology and hence would entail greater cost and risk.

Of the remaining applications identified in Table 5-1, the MMIC channel amplifier, according to the analysis on this program, has cost benefits in comparison with the present hybrid approach. But since it does not promise benefits beyond this cost savings, it seems to be an application best left to industry to develop or not depending on its perception of the cost tradeoffs.

The X-Band anti-jam antenna would be of benefit to the military, and the analysis on this program illustrates the benefits of MMICs to active arrays in general. However, the development of MMICs for this application should be done by the military.

Finally, the on board signal processing application is a difficult one for this program to evaluate. In the first place, as a digital circuit technology, it does not accurately fit into the category of MMICs, although as was pointed out, the use of GaAs integrated circuitry promises significant benefits. In addition, although GaAs bulk demodulators promise impressive weight and power consumption advantages in comparison to silicon VLSI, except for a possible Data Distribution Satellite, the benefits are mainly applicable to future

communication satellite systems to serve mobile and very small aperture terminals. Thus, although the benefits promise to be significant enough to justify development, whether the development is in the province of NASA or private industry must be answered by considerations beyond the scope of this project.

6.0 RECOMMENDATIONS FOR NASA DEVELOPMENT

On the basis of the considerations discussed in Section 5 of this report, it is possible to outline an MMIC development program to support the requirements identified by this study. This proposed program is summarized in Table 6-1 and described in more detail in the following paragraphs.

6.1 MMICS FOR MILLIMETER-WAVELENGTH ACTIVE ARRAYS

Section 5 of this report discussed the fact that the commonality of several important applications makes it clear that the development of efficient power amplifier MMICs in the 20 to 60 GHz range is a high priority goal.

Specifically, 32 GHz power amplifiers with at least 100 milliwatts output and an efficiency greater than 30% are needed for interplanetary probe applications such as the Cassini mission (Saturn Orbiter/Titan Probe) and the Mars Sample Return. The efficiency is extremely important in this application particularly for the Cassini probe since power savings in comparison to an X-Band approach is a major driver for the 32 GHz system. The power amplifiers will be used in arrays for electronic beam steering. A possible implementation of the Cassini probe would use 21 elements, spaced by about 1.7 cm, each producing 100 milliwatts with a power added efficiency of at least 30%. The Mars Sample Return would also use an array but with many more elements.

For the Space Station a steerable multibeam antenna for communication with users in the control zone would require large numbers (several hundred) of power amplifiers for a transmitter array. Frequency would be 21-23 GHz. 2 Watts of output power with 15 dB gain at a power added efficiency of greater than 30% is required. The technology for such MMICs would also be capable of providing power amplifiers for communication satellite arrays for scanning spot beam downlinks.

This development program will also advance the capability for 60 GHz power amplifiers. Such devices are needed both as elements for active arrays for intersatellite links and as elements which can be combined in a passive combiner to produce 5 to 10 Watts to feed a dish antenna in an intersatellite link.

Power HEMT devices now seem to be the most promising approach for these power amplifiers. However, a risk of this approach is the unproven reliability of these devices. A promising backup approach is the Heterojunction Bipolar Transistor (HBT). Since the development of efficient power amplifier MMICs for these frequencies is the key to the success of important systems for both NASA and the military, both power HEMT and HBT approaches, at a minimum, should be supported to reduce risk.

Although the power amplifier is the critical development, and other important elements of the active arrays have already received attention, some important issues remain. Phase shifter technology is not yet adequate. Improvement needs to be made in the designs to make the insertion loss less sensitive to the phase setting. A development program should develop 21-23 GHz or 32 GHz phase shifters with loss variation less than 0.5 dB, as is theoretically possible element, providing heat sinking to the active devices and distributing the RF and control signals to the MMIC elements. The use of optical fibers for distribution of the RF and control signals may be an important part of the solution to this problem. NASA-Lewis recognized the importance of this technology and has already taken the lead in developing optical electronic integrated circuits. It is also possible that the new high temperature superconductors will play an important role in solving this antenna array control problem. This problem area will be studied, for 20 and 44 GHz arrays, under a planned RADC program. This work should be followed closely and supplemented if it seems appropriate.

6.2 PHASE SHIFTER FOR TDRSS ON BOARD BEAMFORMING

The development of a 2.29 GHz phase shifter would be a valuable contribution to future improved versions of TDRSS. On board beam forming would facilitate handling a greater number of users and antenna elements, and would eliminate possible problems resulting from differential phase shifts between the signals transmitted to the ground for processing in the present approach. However, on board beam forming adds considerable complexity aboard the satellite. This study has shown that, based on a typical scenario requiring 762 phase shifters on the satellite, hybrid MIC phase shifters would add over 28 kg to the weight of the satellite, whereas MMIC phase shifters would add only 3.7 kg. Thus, the MMIC approach could be crucial to making on board beam forming practical. It is considered a low risk development based on present MMIC technology, and its development would be helpful in demonstrating that MMIC is a viable technology.

6.3 PHASE SHIFTER AND AMPLIFIER FOR SYNTHETIC APERTURE RADAR

An important need exists to reduce the weight of a space based synthetic aperture radar such as would be used for Mission to Planet Earth. MMICs could make a major contribution to this objective, but need to prove their capability by demonstrating the ability to produce a significant number of repeatable, reliable, full-spec devices. The recommended program would develop digital phase shifters and small signal amplifiers for the C-Band radar (5.3 GHz) and would produce enough units to demonstrate the reproducability of the process. A more ambitious program would develop also the power amplifiers (12 Watt peak, 1 Watt average) and low noise amplifiers (< 2 dB noise figure) for 5.3 GHz.

6.4 DEVELOPMENT OF SUPPORTING TECHNOLOGY

A typical characteristic of microwave circuit requirements for space applications is that a high premium is placed on reliability and minimizing weight, characteristics which argue for the use of MMIC technology. On the other hand it is also characteristic of most space applications that the quantity required of any particular circuit is very small and tight electrical performance specifications must be met. These latter characteristics generally are incompatible with the MMIC approach because the high development costs of custom MMICs cannot be spread over a large number of units.

Therefore, a valuable contribution to making MMICs available for space applications is design tools which would greatly reduce the cost of MMICs for high performance, very small quantity applications. The Application Specific MMIC approach described in Section 4 is a promising approach to this need. Development of this approach may be supported to some extent by the military, for whom this approach also has potential value. Developments along these lines should be followed carefully to see how adequately the program funded by the military supports NASA needs with serious consideration given to supplementing the military program as needed, for instance by developing an ASMMIC "footprint" usable for NASA programs.

TABLE 6-1

RECOMMENDED MMIC DEVELOPMENT PROGRAM

APPLICATION	DEVELOPMENT	COMMENTS
Millimeter-wavelength Active Arrays (Space Station, Interplanetary Probes, Communication Satellites with Scanning Spot Beams, Anti-jam Antennas)	1. Efficient Power Amplifiers (22, 32 GHz, > 30% efficiency) 2. 5-bit Phase Shifters with Minimum Insertion Loss Variation 3. Array Backplate Technology	Overlapping military and NASA needs require coordination and cooperative development Recommend HBT as backup to prime HEMT approach for efficient power amplifiers
Tracking and Data Relay Satellite System (TDRSS)	2.29 GHz Phase Shifter	Low risk development, important benefit to program, helps to establish MMIC as viable technique
Synthetic Aperture Radar (Mission to Planet Earth)	5.3 GHz Five-bit Phase Shifter and Small Signal Amplifer	Also a low risk development, important for reducing weight of array. More ambitious program would develop power and low noise amplifiers as well
General-To Reduce Development Costs for Low Quantity Applications	Application Specific MMICs Advanced CAD tools	

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16. Abstract

This report presents the results of a 17 month study on the future trends and requirements of Monolithic Microwave Integrated Circuits (MMIC) for space communication application. Specifically this report identifies potential space communication applications of MMICs, assesses the impact of MMIC on the classes of systems that were identified, determines the present status and probable 10-year growth in capability of required MMIC and competing technologies, identifies the applications most likely to benefit from further MMIC development, and presents recommendations for NASA development activities to address the needs of these applications.

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